FABRICATION OF PRESSURE SENSING DEVICE TO DETECT TOE WALKING

A Thesis Presented

By

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ABSTRACT

Toe walking is a gait abnormality characterized by a lack of heel contact through stride in a walking gait. Tracking the frequency of this behavior to guide and/or assess therapy methods, would be clinically important. Currently, such tracking is accomplished visually by a therapist during intervention sessions, but outside these sessions data is anecdotal, and provided by family members. To improve on this, a previous capstone design project created a device to automatically track and record toe and heel strikes during everyday use, while walking in a minimally invasive and virtually undetectable package. While effective, this required irreversible modification to the midsole of the shoes in order for the device to fit. As an attempt at improvement, this work investigated a rubberized insole to encase all necessary sensor electronics. All process and fabrication methods are described, along with several relevant mechanical characterization tests to determine the feasibility and lifetime of the proposed method. Results indicate that both mechanical performance and reliability of this new method are inferior to the capstone design, and explanations for this are discussed.
ACKNOWLEDGEMENTS

Professor Andrew Gouldstone has been with this project from its inception over a year ago with our undergraduate capstone group that started this all. I cannot thank him enough for the amount of work that he has put in above and beyond any other professor, teacher, or mentor I have met. The original capstone members Jack Elliot, Danielle Goldberg, Stefan Gottschalk, and Patrick Murphy were the ultimate dream team to work with and together laid an extremely strong foundation for this thesis work through capstone. Adam-Ridgley Khaw and Dan Raynor at New Balance and Instron, respectively, were always helpful and knowledgeable in the repeated characterization and testing of the device as well as typical shoe testing methods. The analysis of the projects would not have been possible without them. Finally, my friends and family have been ever supportive with the number of hours dedicated to this investigation and its documentation. Thank you for the motivation and constant understanding.
# TABLE OF CONTENTS

1. **Introduction** .............................................................................................................. 1

2. **Background** .................................................................................................................. 1
   2.1. **Project Need** ......................................................................................................... 1
       2.1.1. Toe Walking as a Behavior ................................................................................ 1
       2.1.2. Complications and Correction ............................................................................. 2
   2.2. **Capstone Design** .................................................................................................... 3
   2.3. **Capstone Recommendations** .................................................................................. 4

3. **Thesis Design** .............................................................................................................. 5
   3.1. **Rubberized Insole** ................................................................................................ 5
       3.1.1. Size and Shape .................................................................................................... 5
       3.1.2. Material and Durometer ...................................................................................... 6

4. **System Analysis** ......................................................................................................... 9
   4.1. **Impact Cushion Testing** ....................................................................................... 9
   4.2. **Underfoot Pressure Testing** ................................................................................ 11
   4.3. **Lifetime Durability Testing** ................................................................................ 12

5. **Discussion** .................................................................................................................. 14
   5.1. **Device Comparison** ............................................................................................. 14
       5.1.1. Impact Testing .................................................................................................... 14
       5.1.2. Pressure Testing ............................................................................................... 14
       5.1.3. Lifetime Durability ........................................................................................... 15
       5.1.4. Further Design Comparison and Analysis ......................................................... 16
   5.2. **Future Work** .......................................................................................................... 25

6. **Conclusion** .................................................................................................................. 27

7. **References** ................................................................................................................. 29
LIST OF TABLES

Table 1: Impact testing results. ................................................................. 10
Table 2: Calculated elastic modulus of Shore A silicone rubbers. .................. 22
Table 3: FEA model results for varying materials and thicknesses. (Scale is the same as
  Figure 29 and Figure 31)........................................................................... 23
LIST OF FIGURES

Figure 1: Capstone project final design showing modified shoe and electronics packaging. ................................................................. 3
Figure 2: Detailed electronics view with micro SD card, Lightblue Bean, and coin cell battery. ............................................................... 3
Figure 3: SolidWorks model and actual picture of 3D printed electronics case. .......... 4
Figure 4: Closeup of shoe modification for 3D printed case. ........................................ 4
Figure 5: 3D printed case installed into shoe modification. ........................................ 4
Figure 6: Model of shoe insole in SolidWorks. .......................................................... 6
Figure 7: Machined Aluminum mold for insole. .......................................................... 6
Figure 8: Shore Hardness Scale used in initial material selection (Shore A scale used). [13] ........................................................................................................ 7
Figure 9: Molding setup of 30A Smooth-On Urethane inside of Fume Hood. ............... 7
Figure 10: 40A McMaster-ordered insole with molded electronics. ............................. 8
Figure 11: 30A Smooth-On urethane rubber insole with molded electronics. ............... 8
Figure 12: OOMOO Silicone Rubber mold with electronics. ........................................ 9
Figure 13: Impact testing setup at New Balance. .......................................................... 10
Figure 14: (Left) Composite insole used for pressure testing. (Right) Tekscan F-Scan sensor adhered to insole. ................................................................. 11
Figure 15: Test user walking with device and TekScan F-Scan system operational. ... 11
Figure 16: Left (No device) and Right (Device) pressure maps from rubberized insole trial run with F-scan system. ................................................................. 12
Figure 17: Shoe with installed rubber insole device on E3000 machine. ....................... 12
Figure 18: From left to right, the silicone rubber insole; Installed inside of the shoe; and the fully assembled durability shoe................................................................. 13
Figure 19: Data collection during lifetime testing. ....................................................... 13
Figure 20: Left (No device) and Right (Device) pressure maps from capstone hard case trial run with F-scan system................................................................. 15
Figure 21: Delamination of Bluetooth communication chip on Bean. .......................... 16
Figure 22: Simplified cross section representations of (a) unmodified shoe, (b) shoe with capstone device inserted, and (c) shoe with rubberized insole. ......................... 17
Figure 23: Capstone device SolidWorks Simulation results

Figure 24: LEFT: Side view of Lightblue Bean electronics board. RIGHT: Shear force (shown in teal arrow) through rubber (purple) acting on electronics (black) apart from the printed circuit board (PCB, green).

Figure 25: SolidWorks model showing outline of electronics embedded inside of insole.

Figure 26: SolidWorks model of insole showing fixture constraints.

Figure 27: Loading scenario for rubberized insole FEA model.

Figure 28: Visual of localized mesh control used to investigate cross section. Note finer mesh on surface presented in front of image and coarser mesh towards the far end of the insole.

Figure 29: Equivalent strain of 30 Shore A insole under load.

Figure 30: S-N curve for UNS G41300 Steel. [18]

Figure 31: 0.25" thickness 60 shore A rubber insole FEA model result in equivalent strain.

Figure 32: 60 Shore A rubber insole with 0.01" thick ABS plate adhered to surface.

Figure 33: 0.025" 20 Shore A rubber, 0.01" ABS plate, 60 shore A rubber insole stack. (Same scale as Figure 32).
1. Introduction

This thesis evaluates the viability of an alternative electronics packaging design based on the toe walking measurement device developed in the undergraduate capstone project “Device to Aid in the Correction of Toe Walking in Children with Autism” [1]. The electronics package developed through this capstone project is housed in a 3D printed plastic case and requires substantial modification to the midsole of the shoe for installation. To ease installation of the device, it was hypothesized that a complete package could be incorporated into an unmodified shoe. This would reduce the need for skilled labor in modification of the shoe or a unique molded midsole, and allow modularity of the device between shoe sizes and types. A rubberized insole-shaped device was developed to test this hypothesis. Comparative quantitative testing was performed for mechanical characterisation and quantitative comfort analysis. The data is presented and a recommendation for future work is drawn from the comparison.

2. Background

2.1. Project Need

Toe walking is a bilateral gait abnormality characterized by a lack of dorsiflexion during the ground contact portion of the gait; meaning the person exhibiting this gait does not touch their heels to the ground while walking. This behavior is exhibited in many different populations including those with cerebral palsy (CP), autism spectrum disorder (ASD), toddlers who exhibit idiopathic toe walking (ITW), and others with neurodevelopmental disorders. Toe walking in CP is a single factor of a much more complex gait caused by the muscular effects of the disorder: hemiplegia, equinus foot, and spasticity can all be associated along with toe walking [2]. Due to this complexity, specialized gait labs are used to accurately model the movement of the entire leg and determine the proper course of treatment. ITW is a behavior of unidentifiable origin that presents and disappears with many children while they are learning to walk [3]. Toe walking is observed in approximately 20% of people with ASD [4], [5].

2.1.1. Toe Walking as a Behavior

Different from CP or ITW, the etiology of the toe walking behavior associated with ASD has multiple theorized causes. An important note here is that toe walking exhibited by people with ASD is a behavior – while the exhibitor does not choose to toe walk, they are not physically
incapable of putting their heel down either. One theory attributes the behavior to a sensory deficit in people with ASD [6]. Toe walking in this case would require tightening the gastrocnemius to lock the ankle in full plantar flexion on contact with the ground, eliminating the spring-like role the ankle plays in bipedal movement. Without this anatomical ‘spring’, more force is transferred directly through the leg, causing the person to experience a greater sensation from the event. Another theory involves the vestibular system and bodily awareness [7]. The vestibular system is responsible for the connection between the brain and body position; it may be thought of as the ‘sensor’ in a closed loop control sequence for determining body position. To continue the metaphor, in autism this ‘sensor’ is calibrated incorrectly, sending incorrect body position to the brain, which compensates with the toe walking behavior.

2.1.2. Complications and Correction

This behavior (also called a stereotypy due to its repetition in the exhibiting autism population) has several negative associations that justify correction. For one, toe walking is an instable gait that can cause an increase in falls. Additionally, this stereotypy carries a social stigma that negatively affects the already compromised ability of a person with autism to interact socially. This reason drove the compact and discreet design constraint of the capstone project discussed later on. Over time, persistent toe walking can cause spasticity in the lower leg that physically prevents a typical walking gait and may require surgery [8]. Physical, occupational, and behavioral therapy are all used to correct toe walking as a behavior associated with autism. Behavioral treatments include stretching, ankle-foot orthotics (AFOs), and behavior reversal using reinforcement techniques [9], [10], [11]. A major factor of determining the efficacy of treatments is tracking the frequency of toe walking over the course of application. Currently this is achieved through visual observations during therapy sessions which occur approximately twice per week for 45 minutes each [12]. This system leaves a lot to be desired in terms of walking data. Therapy sessions are a small representation of a patient’s weekly walking regiment and the visual observations are prone to human error. Out of session data is based on anecdotal observations by parents or caretakers. This leaves a gap in data collection that the capstone project discussed below aims to fill.
2.2. Capstone Design

The previous design is a force sensing shoe consisting of two force sensitive resistors attached to the bottom of the insole as seen in Figure 1. The sensors output a voltage based on the forces applied to the sensing region. These are connected via analog ports to a Lightblue Bean, an Arduino based Bluetooth programmable microcontroller with a small form factor, that also includes an on-board accelerometer and temperature sensor in addition to input and output ports. Data produced from the force sensors is then written over digital output ports to a text file on a micro SD card, which stores the data until it is removed from the device and plugged into a computer. The entire package is powered from a 3.3V coin cell battery. A detailed view of the electronics can be seen in Figure 2.

The case was designed in SolidWorks and manufactured using 3D printing for rapid iterations of case designs and its accessibility during the design cycle. A screen shot of the design in SolidWorks can be seen next to a picture of the actual case in Figure 3. A close-up of the midsole
modification necessary to fit the case can be seen in Figure 4. The missing portion of the midsole was cleaned out with an ultrasonic knife and a Dremel tool.

Figure 3: SolidWorks model and actual picture of 3D printed electronics case.

Figure 4: Closeup of shoe modification for 3D printed case.

Figure 5: 3D printed case installed into shoe modification.

2.3. Capstone Recommendations

The capstone team recognized the room for improvement with this device. For example, for a commercial application, a custom flexible printed circuit was recommended. This would drastically reduce the thickness of the assembly and increase manufacturability. In addition, a
rechargeable battery was recommended in order to increase usability. Batteries charged wirelessly through inductive charging coupled with Bluetooth programming and data transfer would allow a single device insertion, and reduce the need for it to be removed from the shoe. This thesis attempted the initial steps toward such a flexible structure, as described in the next section.

3. Thesis Design

It was determined that a truly ‘flexible’ electronics design could be achieved via a number of combinations, that did not necessarily require a printed circuit board to achieve. For example, implementation of modular electronic components into a flexible structure could achieve the goals of (i) improved manufacturability and (ii) improved reliability. Accordingly, in this thesis, a rubberized insole was designed to house the existing electronics. The existing electronics are highly modular due to their simple programming platform, Bluetooth wireless capability, and range of input/output ports. Continuing work with this electronics package allowed more intense focus on the mechanical design of the device.

3.1. Rubberized Insole

Inspiration for this design was drawn from common gel inserts that are widely available at typical pharmacies. The shape of these inserts mimics that of a shoe insole for seamless integration into the shoe. This form was chosen for the device insert to minimize impact of the device and maximize comfort for the user.

3.1.1. Size and Shape

For this project, exact measurements were taken of the insole of a child size 12 shoe and used to create a SolidWorks model, shown in Figure 6. This shoe size was chosen based on the shoe and size used in mechanical characterization in the undergraduate capstone project. Utilizing the same shoe make, model, and size allowed for a direct comparison of data during mechanical characterization. Based on these measurements, an aluminum mold was CNC machined for prototyping, shown in Figure 7. Draft angles were included and appropriate tooling was implemented to achieve a fine surface finish for ease of release.
3.1.2. Material and Durometer

The constraints of the device environment placed a narrow range on the possible materials and their durometers. Emulating commercially available comfort insoles, a rubber-like material was sought to provide cushioning for the user in addition to protecting the electronics. A two-part rubberized material was selected for its ability to be poured over and cure around the non-uniform electronics inside the machined mold. The first material selected was a two-part liquid urethane rubber, chosen based on its wide range of available durometers, short lead time, and short cure time for rapid development.

Material durometers were selected on the shore A hardness scale using a comparative chart shown in Figure 8. A medium range between the hard electronics and the soft midsole of the
shoe being tested was sought. While the commonly found gel shoe insole is comprised of an extra soft material as shown in the chart, a harder material was selected for the device insole to provide more protection to the electronics while maintaining comfort for the user.

![Shore Hardness Scales](image_url)

**Figure 8**: Shore Hardness Scale used in initial material selection (Shore A scale used). [13]

All molds presented were poured and cured in a fume hood setup as in Figure 9. Insoles were molded out of both 40A and 30A liquid urethane rubber for initial testing, seen in Figure 10 and Figure 11 respectively. Both insoles were inserted into the shoe and subjected to a preliminary feel test.

![Molding Setup](image_url)

**Figure 9**: Molding setup of 30A Smooth-On Urethane inside of Fume Hood.
Figure 10: 40A McMaster-ordered insole with molded electronics.

Figure 11: 30A Smooth-On urethane rubber insole with molded electronics.

Here the 30A durometer was deemed a more appropriate choice moving forward. Additionally, the 40A urethane (obtained from McMaster) needed to be heated to 120°F to obtain a reasonable cure time of 24 hours; otherwise, it was a seven-day cure time at room temperature [14]. 30A urethane from the Smooth-On company boasted a room-temperature 18-hour cure which better suited the thesis needs.

A spray-on mold release was utilized for the urethane to allow for easy device removal. As seen in Figure 11, the urethane castings were not perfectly uniform and ended up with large bubbles and voids in the finished product. OOMOO silicone rubber by Smooth-On was identified as a replacement due to its independence of mold releases and similar mechanical properties [15]. As
seen in Figure 12, the silicone rubber device insole produced a much more uniform product and did not require any release agents.

![Figure 12: OOMOO Silicone Rubber mold with electronics.](image)

4. System Analysis

The molded rubber insoles fabricated were tested using multiple different methods and machines to compare their mechanical characteristics and performance to the prototype from the undergraduate project. Urethane insoles were tested at the New Balance sports research facility in Lawrence, MA for impact characteristics and foot pressure analysis. The silicone rubber mold was tested at the Instron headquarters in Norwood, MA for lifetime durability analysis.

4.1. Impact Cushion Testing

Cushioning underneath the user’s foot, specifically the heel, is of utmost importance in this case due to the location of the electronics package. A standard piece of testing equipment used to analyze shoes is the impact cushion testing machine shown in Figure 13. The brass weights shown in the top of the image can be adjusted according to user weight. In order to directly compare the device to its predecessor, the weights were kept at 5700 g representing a 170lb person. The weighted rod assembly was dropped from calibrated distances of 30 and 50 mm to simulate walking and running, respectively.
The numerical results of the testing are shown in Table 1 along with testing results from the identical capstone testing. Cushioning was determined from the average peak deceleration over 5 impacts. Lower peak deceleration signified greater cushioning.

Table 1: Impact testing results.

<table>
<thead>
<tr>
<th>Impact Criteria</th>
<th>Assembly Tested</th>
<th>Average Peak Deceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walking</td>
<td>Unmodified Shoe</td>
<td>8.79</td>
</tr>
<tr>
<td></td>
<td>Capstone Modified Shoe with Device</td>
<td>10.49</td>
</tr>
<tr>
<td></td>
<td>New Balance Running Shoe</td>
<td>10.45</td>
</tr>
<tr>
<td></td>
<td><strong>Rubber Cast Electronics Shoe</strong></td>
<td><strong>8.60</strong></td>
</tr>
<tr>
<td>Running</td>
<td>Unmodified</td>
<td>11.33</td>
</tr>
<tr>
<td></td>
<td>Capstone Modified Shoe with Device</td>
<td>15.38</td>
</tr>
<tr>
<td></td>
<td>New Balance Running Shoe</td>
<td>14.92</td>
</tr>
<tr>
<td></td>
<td><strong>Rubber Cast Electronics Shoe</strong></td>
<td><strong>11.09</strong></td>
</tr>
</tbody>
</table>
4.2. Underfoot Pressure Testing

A composite insole was fabricated to represent the electronics in a size 10 men’s shoe, shown in Figure 14. The TekScan F-scan system was adhered underneath the actual shoe insole which was then installed on top of the rubber device insole inside of the shoe. This allowed pressure data to be gathered in the same fashion as the previous capstone project.

The device was installed into the right shoe while the left shoe was unaltered. The user for this test walked on a treadmill with the F-scan system strapped onto their ankles and waist, as seen in Figure 15. No discomfort was reported during the test. Data was collected in the form of calibrated pressure maps of the shoe area. Pressure was calibrated from user weight measured at the facility directly preceding the test.
Comparative pressure data from the run is shown in Figure 16. There is a clear increase in pressure (shown by the larger red area) on the right foot in the heel region where the electronics are located in the insole. There is relatively low variation in the pressure around the metatarsal phalangeal joints.

![Figure 16: Left (No device) and Right (Device) pressure maps from rubberized insole trial run with F-scan system.](image)

4.3. Lifetime Durability Testing

![Figure 17: Shoe with installed rubber insole device on E3000 machine.](image)

An Instron E3000 machine was used to test the lifetime durability of the prototype. The silicone rubber insole device was put inside the test shoe underneath the stock insole. The device was held with a standard shoe fixture used for previous clients in the laboratory as seen in Figure 17. The insole device and final testing configuration can be seen in Figure 18. A 50mm platen was
positioned directly over the electronics in the heel of the shoe. Compression Loading was cycled between 50 and 150lbs at 1Hz over the course of 5 days.

When the Instron machine test started, the device electronics began writing heel and toe sensor data to the onboard SD card. After ending the Instron machine test, the data was graphed vs. time. Detailed notes were taken to ensure that the proper number of cycles were recorded on the electronics. Device data can be seen in Figure 19. The data shows that the device ceased to record data after approximately 18,000 cycles.
5. Discussion

Each toe walking measurement device; the one developed in the undergraduate capstone project and in this thesis investigation, was put through a range of characterization testing for direct comparison.

5.1. Device Comparison

5.1.1. Impact Testing

The data in Table 1 clearly shows that the capstone shoe system decreased the amount of cushioning in the shoe while staying around limits of commercially available running shoes. The shoe with the rubber cast electronics insoles shows an increase in the amount of cushioning over the original shoe in both the walking and running scenarios. These results can be expected due to the construction and modifications necessary to the shoe in each design.

In the capstone design, cushioning material is removed and the volume is replaced by a hard plastic plate covering the electronics. Impact energy is not as readily absorbed by this stiff structure as it is by the soft foam that was removed. While this was not ideal for the user, it was shown through further testing that the cushioning fell within the range of typical running shoes. Alternatively, the rubberized insole added a cushioning material underneath the heel without removing any of the existing cushion. While the hard electronics assembly was still present, the overall cushioning was increased from the unmodified shoe due to this addition. While these results are critical, the impact cushioning is not all encompassing as the foot is also sensitive to gradients in pressure due to the materials underfoot.

5.1.2. Pressure Testing

Figure 20 shows the pressure maps of the capstone project device test with the F-Scan system. It can be seen that the pressure in the heel where the hard case is located increases in size and intensity from the unaltered left foot map to the right foot map with the device installed. While both the capstone device and thesis device insole increased under-heel pressure, the stark difference between the images in Figure 16 compared to the slight increase between images in Figure 20 show that the capstone device created less of a pressure point.
Figure 20: Left (No device) and Right (Device) pressure maps from capstone hard case trial run with F-scan system. This characteristic can be attributed to the weight distribution top designed into the hard case acting as a plate supported along the edges by the midsole. By transferring the weight through the case into the rest of the midsole, areas of high pressure were avoided. With the thesis insole device, the rubber of the insole was being compressed directly by the heel. Only a thin layer of the rubber covered the harder electronics. When compressed, the rubber above the electronics deflected and transferred the force directly into the electronics. This created an area of higher pressure and therefore an area of discomfort for the user. More explanation of the load path in this assembly is discussed in section Error! Reference source not found...

5.1.3. Lifetime Durability

Previous findings with the capstone device showed that two different prototypes lasted upwards of 40,000 and 100,000 cycles respectively. Alternatively, the insole device from this investigation lasted only 18,000 cycles. In both tests, the battery was confirmed to not run out during the test by recording the voltage with a voltmeter and failure was attributed to other factors in the electronics. Upon close examination of the electronics that were cast in the rubber insole, there was no visible failure of any of the electronics or the printed circuit board (PCB). Some delamination of the Bluetooth chip on the Bean was observed, as seen in Figure 21. This presents evidence that it is not compression that causes failure, but a difference in shear experienced between the PCB (which should experience very little shear) and the rubber insole.
(which would experience a lot of shear) that causes individual electronics components to become separated from the PCB and ultimate failure.

![Figure 21: Delamination of Bluetooth communication chip on Bean.](image)

Focusing on the load path, the rubber insole device looks to cushion the forces experienced in the shoe with surrounding material. Electronics are placed directly in the load path and the forces are expected to transfer through the softer rubber around them. The hard plastic case of the capstone device transfers most of the forces around the electronics by using the existing shoe infrastructure as a support. Distributing the weight in this manner takes the electronics out of the direct load path and are damaged only when the casing fails. A more detailed comparison of the two structures can be discussed with a higher degree of detail using computer modeling.

5.1.4. **Further Design Comparison and Analysis**

To analyze the load path through the assembly in the shoe, it is beneficial to look at a lateral cross section of the shoe under load. Figure 22 shows multiple cross sections of the different configurations of the shoe. Blue arrows represent forces by the user. The grey section is the stock shoe insole, and the black area is the midsole of the shoe. In Figure 22 (b) and (c), the electronics are represented by the blue rectangle. Representing the capstone device, Figure 22 (b) shows the case in red. The rubberized insole is represented by the purple area in Figure 22 (c).
Figure 22: Simplified cross section representations of (a) unmodified shoe, (b) shoe with capstone device inserted, and (c) shoe with rubberized insole.

In an unmodified shoe, force is applied over the contact area of the heel on the shoe insole and distributed through the midsole and to the ground, as seen in Figure 22 (a). Figure 22 (b) shows how the force is applied to the top plate of the capstone device, supported by the shoe midsole. Note the amount of space separating the electronics from the loaded plate of the case, highlighted by the green circle. This ‘crush zone’ gives a certain amount of space that the case can deflect before the electronics are loaded.

A simple finite element analysis was run for this case using SolidWorks Simulation software, the results of which can be seen in Figure 23. This particular simulation was setup to mimic the lifetime testing at Instron previously discussed in section 4.3. A 150lb load was applied over a 2in² area representing the compression platen used on the Instron machine. An elastic foundation with a uniform elastic modulus equal to that of EVA foam (commonly used foam in shoe
insoles) was used to support the case. The results show that the case has a maximum deflection of 0.08mm, which is approximately 4% of the crush space in the design.

Figure 23: Capstone device SolidWorks Simulation results.

Figure 22 (c) clearly has a lack of this ‘crush zone’, however it does have the cushion of the rubber insole on top of the electronics. While this provides some level of protection, there is a component of the force that is transferred through the electronics at all times rather than only after the crush zone is depleted. This is a key element to protecting the electronics.

Different from the plastic case, the rubber insole focuses on reducing the amount of strain seen on the individual electronics fastened to the surface board. The physical circuit board is a robust material composed of layered epoxy fiberglass and copper with a flexural modulus of 19 GPa [16]. Figure 24 shows a side view of the significance of the raised electronics off the circuit board. By minimizing the amount of strain seen on the barrier between the rubber (purple) and PCB (green) the elastic gradient between the two materials can be reduced and and the assembly can become more robust.

Figure 24: LEFT: Side view of Lightblue Bean electronics board. RIGHT: Shear force (shown in teal arrow) through rubber (purple) acting on electronics (black) apart from the printed circuit board (PCB, green).
A SolidWorks model was developed similar to the lifetime test performed at Instron to represent a real-life loading scenario. To do this, a solid representing the electronics was modeled with the material properties of FR-4, a common PCB material. Material properties for the silicone rubber were calculated from the following conversion from Shore A durometer to the Elastic Modulus [17]:

\[
\text{Elastic Modulus [MPa]} = e^{0.0235(S\text{hore } A \text{ durometer}) - 0.6403} \tag{1}
\]

The insole was directly based on the SolidWorks model of the mold that was machined for casting to ensure accuracy. The electronics were modeled inside of the rubber insole as seen by the outline in Figure 25.

![Figure 25: SolidWorks model showing outline of electronics embedded inside of insole.](image)

The bottom surface of the mold was constrained in the Y direction to allow the material to slide around, however the curved edges needed to be constrained in all directions as seen in Figure 26. A total loading force of 150 lbf was applied to a 2 inch circle on the topmost surface of the insole to mimic regular loading as seen in Figure 27. A plane was placed laterally across the center of the load area to split the model and create a cross section that could be viewed for an in-depth strain analysis. All the contacting surfaces between different bodies of the model (e.g. rubber insole and electronics) were bonded together, meaning that both parts acted as one solid body with different material properties.
Figure 26: SolidWorks model of insole showing fixture constraints.

Figure 27: Loading scenario for rubberized insole FEA model.
Mesh control in SolidWorks Simulation was used to refine the mesh in the cross section bisecting the load area that was mentioned before. A finer localized mesh was used to get a better idea of the strains experienced on this plane while a coarse mesh was used on the rest of the model to reduce computation time. The mesh used can be seen in Figure 28.

![Figure 28](image)

Figure 28: Visual of localized mesh control used to investigate cross section. Note finer mesh on surface presented in front of image and coarser mesh towards the far end of the insole.

To begin with, a model was created using 30 Shore A durometer silicone rubber, which was the material used in the lifetime testing previously discussed. Figure 29 shows a very high strain gradient from the electronics (blue rectangle in center of cross section) to the surrounding rubber, which is experiencing 5% strain and higher. This provides sound evidence that high strain was the cause of premature (18,000 cycle) failure in the previously performed lifetime testing.

![Figure 29](image)

Figure 29: Equivalent strain of 30 Shore A insole under load.
While the testing performed at Instron is capable of obtaining physical data on cycle count and device failure, it is also time consuming and difficult to schedule. With the strain failure theory from our initial experiment there matching up with the SolidWorks simulation model discussed above, multiple rapid iterations can be assessed in the software to determine a successful path for future iterations of this model. Two major criteria that can be assessed for impact in this particular device are the durometer of the rubber used and the thickness of the insole. By using equation 1, we can obtain the material characteristics needed to perform an elastic analysis on other models for a variety of different durometers. Silicone rubbers of shore A durometer 20, 30, 40, 60 and 90 were tested. The resulting elastic moduli can be seen in Table 2.

<table>
<thead>
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<th>Durometer (Shore A)</th>
<th>Elastic Modulus (Mpa)</th>
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</tr>
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<td>40</td>
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<td>60</td>
<td>2.16</td>
</tr>
<tr>
<td>90</td>
<td>4.37</td>
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</tbody>
</table>

Each of these materials was tested with increasing insole thicknesses as well. The base insole that was manufactured and tested at Instron was a maximum of 0.25 inches thick. Maximum insole thicknesses of 0.275, 0.3, 0.35 and 0.4 inches were also tested in the model. Table 3 shows the cross sectional FEA results of each of these model runs. It is clearly visible that as durometer is increased in the rubber around the electronics, the strain gradient decreases towards zero. In the rubber insole model that is 0.25 inches thick made of 90 shore A durometer silicone rubber, we see approximately 1% strain at the surface where the electronics are located. This is an 80% decrease in strain from our 30 shore A rubber model.
Table 3: FEA model results for varying materials and thicknesses. (Scale is the same as Figure 29 and Figure 31).

<table>
<thead>
<tr>
<th>Thickness (Inches)</th>
<th>0.25</th>
<th>0.275</th>
<th>0.3</th>
<th>0.35</th>
<th>0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durometer (Shore A)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>![Image]</td>
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<td>40</td>
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<tr>
<td>60</td>
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<td>90</td>
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<td>![Image]</td>
</tr>
</tbody>
</table>
We can use this model to predict device outcomes in lifetime testing by relating this strain to the number of cycles experienced in our fatigue test. According to Hooke’s Law relating to stresses ($\sigma$) and strains ($\varepsilon$),

$$\sigma = E\varepsilon \quad (2)$$

where $E$ is the elastic modulus (in our case treated as constant). We can use this relationship to study the dynamic fatigue (stress-cycle) curve of a common material such as steel and compare the stress-cycle relationship in that curve to the strain-cycle relationship we are growing here.

![Figure 30: S-N curve for UNS G41300 Steel. [18]](image)

Studying Figure 30 it is noticed that the fatigue strength, which is the amount of stress experienced at the failure after the provided number of cycles, is only approximately 50% higher at $10^4$ cycles than $10^6$. Therefore, it can be inferred that a 50% reduction in our strain values that caused failure at a life on the order of $10^4$ cycles could yield a device that lasted on the order of $10^6$ cycles.

Taking a closer look at the 0.25” thick insole model with 60 shore A durometer rubber FEA result from Table 3 in Figure 31, we can see that the strain on the top surface of the electronics is approximately 2.5%: a 50% reduction in strain from the 5% experienced in the 30 shore A model of the same thickness. Following this logic, it is inferred that the model captured here would last on the order of $10^6$ cycles before failure.
Future Work

Through the use of SolidWorks Simulation FEA modeling, we have already identified potential routes to move forward with the project by simply changing the durometer of the material used to increase the lifetime of the device. The same model was used to incorporate design factors from the capstone project to potentially increase the lifetime even more. By adding a stiffer plate to the top of the rubber, we can further reduce the stress experienced on the surface of the electronics as seen in Figure 32. For this model, the plate was made of 0.01 inch ABS plastic for its light weight and high strength. Note the reduction in bright green area on the front (cross section) face from Figure 31 to Figure 32. This design incorporates the important load distribution plate design from the capstone device case to minimize the strain on the electronics cast in the rubber. However, this modification includes having a harder plastic plate directly underneath the heel of the user, which could decrease the amount of cushioning in the shoe. Considering this again from a user perspective, comfort and cushioning under the heel are both important. With this mindset another feature can be added: an extra layer of rubber on top of this stiffer plate to provide cushioning. From the loading scenarios ran in the FEA model, it was deduced that lower durometer material provided more cushioning while higher durometer material provided more protection. Using this knowledge, a stacked insole consisting of 20 shore
A rubber on top to provide user cushioning, ABS plastic in the middle to distribute load, and 60 shore A rubber underneath can be implemented to protect electronics and minimize strain. The results of this concept are shown in Figure 33. Addition of a softer rubber on top of the ABS plate would increase cushioning underfoot while preserving the load dispersal from the ABS plate. This idea is validated from the impact testing performed comparing the unmodified shoe to the shoe with the 30A rubber insole installed. These would all be worthwhile endeavors to improve the device life and increase performance without custom shoe modification.

Figure 32: 60 Shore A rubber insole with 0.01" thick ABS plate adhered to surface.

Figure 33: 0.025" 20 Shore A rubber, 0.01" ABS plate, 60 shore A rubber insole stack. (Same scale as Figure 32).
5.3. Recommendations

In addition to the future work discussed, there are other ideas discussed during the analysis that could also be beneficial for the device. Looking again at Table 3, stress concentrations form on the top surface of the rubber insole where the edges of the PCB are located in every single insole tested. These are emphasized in Figure 34.

![Figure 34: FEA model highlighting stress concentrations from sharp corners on electronics assembly.](image)

By encasing the electronics assembly in a thin, rounded layer of hard plastic to protect them and using an over-mold technique to fill the rest of the insole with a soft rubber, we could potentially mitigate the stress concentrations on the top surface and provide a more comfortable device for the user. A sketch of this idea can be seen in Figure 35. The white brick in the middle represents the electronics assembly, the green a harder rubber case, and the black a soft rubber completing the insole.

![Figure 35: Sketch of over-molded plastic insole idea.](image)

Another potential benefit to the device would be relocation of the electronics altogether. By moving them out from under the heel, we could avoid the direct load path seen by users stepping with their entire weight on the heel. By studying the pressure maps recorded with the TekScan system during device testing, areas of little to no pressure were identified in the arch area of the
shoe, as highlighted in Figure 36. Removing the electronics from the load path would eliminate the need for more robust electronics protection and increase device lifetime.

![Figure 36: Low pressure areas identified in pressure maps from TekScan pressure testing.](image)

6. Conclusion

Toe walking is a behavior that is currently visually observed by therapists and parents and could benefit greatly from an automated behavior tracking device. Such a device was developed and thoroughly tested throughout the course of an undergraduate capstone project. A set of modified shoes was fabricated and the device was inserted into the customized area of the shoe surrounded by a 3D-printed plastic case. In an effort to minimize fabrication effort and ease installation of the device, a new electronics packaging method was researched and implemented. The form of this was a rubberized insole that inserted into an unmodified shoe. A prototype insole of 30 shore A silicone rubber was fabricated and tested in a similar fashion to the capstone project. An FEA model of this prototype was developed and multiple different durometer materials and insole thicknesses were tested. Based on conclusions drawn from typical dynamic fatigue curves, it was theorized that changing the durometer to a stiffer material would result in better lifetime performance. Using this model, multiple other design features were identified that could increase the life of the device in use.
7. References


