Evaluation of Textile Force-Sensitive Resistors in Quantifying Athletic Shoe Fit

by

Lydia Gaulding Light

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

February 2022

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ABSTRACT

A well-fitting shoe is valuable for many reasons, ranging from daily comfort to prevention of injuries. It is no surprise that a good fit is a driving factor in consumer purchase decisions, and is thus highly prioritized by shoe companies. However, ensuring consistent sizing and fit between shoes of varying shapes, layouts, and materials is challenging. Shoe companies use feedback from volunteer fit testers to adjust the design of new shoes before final production, but this process is time-consuming and provides only subjective information. There is need for a sensor-driven method for shoe companies that can provide accurate and objective data about the fit of a shoe.

There is extensive research on the value and methodology of quantifying shoe fit. Current approaches use dimensional comparison of foot and shoe shapes. However, this technique has its limitations, considering that both the shoe and foot deform differently based on shoe material and shoe-foot alignment. Ideally, fit would be measured when someone is wearing the shoe. There is precedent in research studies for measuring shoe-foot contact pressures with plastic thin-film pressure sensors and using this to successfully quantify shoe fit. However, the physical properties of plastic thin-film sensors are limited and the testing procedure for the sensors used in the studies does not translate well to an industry R&D setting. Instead, this paper investigates the design and use of textile pressure sensors for measuring shoe-foot contact pressures. Textile pressure sensors have been used in embedded socks for measuring plantar pressure in the research of gait analysis, but there is no literature yet on measuring *upper* foot pressures with textile pressure sensors for shoe fit analysis.

A design is proposed for a sensor system with textile pressure sensors that could be used in a shoe company to evaluate shoe fit. The sensor component specifically was investigated further with four prototypes of textile sensors – two prototypes were made with Amradield Stretch conductive fabric, and two were made with Adafruit Knit Jersey fabric; one prototype of each fabric was constructed with 2 ply conductive thread, while the remaining two used 3 ply. The four sensor prototypes were tested with a voltage probe in a voltage divider circuit using standardized weights. Pressures of 20-350 kPa were applied in long-term (45 sec) and short-term (10 sec) tests, and the sensor outputs were evaluated on precision, accuracy, range, and temporal consistency.

All four sensors demonstrated the expected inverse relationship between applied force and resistivity and had an adequate range and temporal precision for testing shoe fit. The results indicate that sensors made of Amradield Stretch performed better in accuracy and precision. There was no significant difference in sensor performance between those with 2 ply and those with 3 ply conductive thread.

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Acknowledgements

I would like to thank Christina Chase, Dr. Barbara Hughey, and Alec Jessiman for their invaluable guidance, patience, and compassion throughout this project. I also extend my thanks to the Mechanical Engineering Department of MIT, including professors, staff, and TAs, for their incredible support both of this project and of my engineering education over the past 5 years.

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1. Introduction

The quality of shoe fit is important for many reasons. Beyond providing daily comfort, proper fit in footwear has been shown to decrease likelihood of developing not only foot pain but also lower limb, hip, and back injuries. Fit is also one of the primary drivers in purchase decisions, and as such shoe companies are highly incentivized to make sure their shoes fit well for the intended size.

However, ensuring consistent sizing and fit between shoes of varying shapes, layouts, and materials is challenging. Shoe companies often use feedback from volunteer fit testers to adjust the design of the shoe before final production, but this process is labor-intensive and only provides subjective feedback. There is a need for a data-collection method that can provide accurate and objective information about the fit of a shoe.

A review of existing literature has revealed that the objective measurement of shoe fit is an issue that many have researched but none have perfected. A driving challenge in this research area is that the shapes of a foot and of a shoe are not static – the foot shape changes when in the shoe and vice versa. This means that a dimensional comparison of the foot and the shoe alone does not capture all relevant information. Data collection would ideally happen when someone is actually wearing the shoe.

A handful of studies have addressed this by using plastic thin-film pressure sensors to measure the foot-shoe contact pressure. This approach to shoe fit has successfully shown that the pressure felt on the foot can be used as an indicator of comfort and proper fit, and that fit issues most often occur on the sides, back, and top of the foot. Depending on the location of the foot, there are different ranges of preferred pressure. However, the physical properties of plastic thin-film sensors are limited and the testing procedure for the sensors used in the studies does not translate well to an industry R&D setting. Instead, textile pressure sensors may have potential for measuring shoe-foot contact pressures in shoe companies.

Based on this existing literature, a design is proposed for a shoe-fit data collection system with textile pressure sensors for use in the context of a shoe company. This design considers a precedent in research and industry for sensor-embedded socks (intended for gait analysis), as well as the specific design requirements of the proposed use case. Four unique textile piezo-resistive pressure sensors were assembled and the viability of these sensors for this design was explored. The four sensors, built with two types of conductive fabric and two types of conductive thread, were tested under long-term and short-term pressure conditions to evaluate precision, accuracy, range, and temporal consistency.

This can inform the design of future shoe-fit data collection systems with textile pressure sensors. Such a system for measuring contact pressures in shoes will push shoe-fit research further and could greatly support shoe companies in producing better-fitting shoes.

2. Background

2.1 The Science of Fitting Shoes

2.1.1 Why Fit Matters

The quality of fit for a shoe is important to both the consumer and the producer. It has been shown that fit and comfort are primary drivers in purchase decisions [1], so there is a strong incentive for shoe companies to have high success rates with customers when it comes to comfort and fit. A study investigating online retail of shoes found that nearly 80 percent of returned running shoes were sent back due to poor fit [2]. Shoe companies have procedures in place to secure the fit of their shoes, and many new technologies are developed specifically for improving comfort. This is especially true in the athletic field, where shoes are often specialized for a particular function, and a properly fitting shoe can either facilitate or hinder better athletic performance.

The fit of a shoe is an important characteristic of comfort, along with features such as suitable heel height and low localized pressure under the heel or ball of the foot [1]. In a study of professional working women, ten features were shown to reliably distinguish between comfortable and uncomfortable shoes. Of these, four were related to the sound, smell, or temperature of the shoe, while the remaining six were consequences of the fit [1]. Similarly, a study of hockey skates showed there was a significant correlation between perceived fit, perceived comfort, and preference for skate boots [3]. Though there are many elements of the experience of wearing a shoe, the fit of the shoe is the most influential aspect of comfort.

Moreover, fit is important for more than just comfort for consumers. Wearing well-fitting shoes can help prevent injuries in work settings, athletics, and casual wear. In a study of work boots for underground coal miners, it was found that bad fits measured at the foot width, first toe, and ball circumference were significantly related to the odds of a coal miner developing ankle pain, foot problems, hip pain, and lower limb pain [4]. Similarly, a study with military personnel found that soldiers given shoe inserts perceived a higher level of comfort and were less likely to develop stress fractures or pain than those without shoe inserts [5,6].

When it comes to athletics, running-related injuries are among the most frequent reasons for primary care visits [7]. In an article about finding the right athletic shoes, orthopedic surgeon Carol Frey said that the "most important message" to convey to patients and athletes is to get the "best fit possible," more so than finding the correct shoe type or newest shoe technology [8].

Even in casual wear, incorrect shoe fit can be a cause for injury. According to the American Orthopedic Foot and Ankle Society Women's Shoe Survey, 80% of the 356 normal female subjects (aged 20-60, with no history of foot-related trauma or illness) had foot pain in the toe or ball region; improperly fitting shoes can put unnatural stresses on the foot, leading to injury and pain [9,10].

Shoe fit matters to consumers because it determines comfort and prevents injury. It follows that shoe fit is a high priority to shoe companies for customer satisfaction and business success.

2.1.2 Shoe Size Validation

The fit of a particular shoe size is known to vary greatly between brand, style, store, and shoe type. Behind the scenes, however, shoe designers and manufacturers are working hard to make each new shoe design fit properly and consistently for the assigned size. During shoe production, this is achieved by using standardized shoe lasts of incremental sizes to manufacture shoes consistently. Some companies also conduct fit testing on new shoe designs with "fit testers," who have the shoe size matching the production sample size (e.g. women's 8 or men's 9). The fit testers try on the prototypes and then answer a series of questions to evaluate the fit and comfort of the shoe. This feedback is used by the designers to tweak the shape or fabric of the shoe before final production. However, this process is lengthy, labor-intensive, and only provides subjective feedback. There is a need for a data-collection method that can provide objective information about the fit of a shoe to supplement survey feedback to better inform the design of new shoes.

2.1.3 Measuring Fit – Dimensional Comparison

The objective measurement of shoe fit is an issue that many have researched but none have perfected. Many different approaches have been taken with varying results, but none have been successful enough to overtake the prevalence of the Brannock device, the classic metal contraption used in shoe stores around the world to determine foot length and width. The Brannock device, however, is a limited representation of the foot shape and is often not sufficient to properly determine shoe fit. Moreover, shoe size and fit with the Brannock device is usually decided on length alone, and thus shoes might be interpreted as a proper "fit" even when other dimensions such as width or arch height are incorrect, resulting in discomfort and pain [4].

Many dimensions beyond length have been defined for the foot, such as instep height, arch height, and ball girth, yet there is no clear consensus on what variable is most important to measure, nor what method is best for measuring it. As stated by one researcher, “it is not easy to make comfortable footwear if the real needs that are related to comfort and the functional requirements are not clearly defined [1].” Nonetheless, the issue continues to be explored by industry and academia alike.

The general approach in studies investigating shoe fit is to determine certain dimensions of the foot and separately of the shoe, and then to compare them. The simplest form of this is linear measurements, as seen in the Brannock device. Other ways of measuring the foot include measuring the horizontal perimeter (2D) [11–13] or getting a volume scan (3D) [1,4], from which other dimensions can be identified. For shoes, taking measurements inside the shoe cavity is difficult so dimensions are usually identified in 3D models of the shoe. This could be a CAD model from product designers [11,13], a shoe last (size-specific blocks used to shape the internal cavity of the shoe during manufacturing) [12], or a 3D scan of a mold casted from the shoe post-production [4]. Once the dimensions of the foot and the shoe are obtained, numerical differences or overlaps of distance, area, or volume can be calculated to quantify the fit.

However, two primary limitations have been identified with these approaches. First, the alignment of both 2D and 3D shapes is challenging and limits the usefulness of comparing measurements [1,3]; e.g. comparing the length of a foot and shoe is an incomplete representation of shoe fit if it is not known exactly where the foot sits in the shoe. Second, the shapes of a foot and of a shoe are not static – the foot shape changes when in the shoe and vice versa [1]. Both feet and shoes have areas of relative rigidity (bone; hard plastic or metal) and relative flexibility (muscle and fat; foam and cloth) that will react differently to dimensional differences or overlaps between the shoe and foot. This means that a simple comparison of the foot shape and the shoe shape does not capture all relevant information. Data collection would ideally happen when someone is actually wearing the shoe.

2.1.4 Measuring Fit – Shoe-Foot Contact Pressure

A different route for measuring shoe fit is to use shoe-foot contact pressure, which has been used successfully to quantify fit [3,14,15]. This approach showed that the pressure felt on the foot from the shoe (the tactile sensation) can be used as an indicator of both comfort and proper fit. The principle behind this is simple: shoes that are too tight will put higher pressures on the foot and can cause pain, whereas shoes that are too loose put lower normal pressures against the foot which can lead to excess friction from the foot sliding around [4]. In a medical study, pressure variables varied significantly between regular and orthopedic shoes and could be used to distinguish between those that fit well and those that did not [14]. This is supported further in literature: differences in pressure magnitude can be used to discriminate between shoe designs and sizes [3,15]. Lastly, it has also been shown that there is a significant relationship between measured pressure, perceived pressure, perceived comfort, and preference [1,3].

These studies also identified that there is a “sweet spot” of pressure that maximizes comfort. The ideal pressure is not zero, but is somewhere between “too tight” and “too loose” [1]. Everyone has an individual range of preferred pressures for each area of the foot. To find a good fit, the pressures at each location on the foot-shoe interface should be in their respective ideal range [1].

In addition, certain areas of the foot are better predictors for comfort and fit than others. The main cause of uncomfortable shoes is the fit in the forefoot region [1]. For example, a shoe that is too small may put “neutral” pressures on the top or sides of the foot that are still in the ideal range for those areas, but will put higher pressure – outside the ideal range – on the sides of the toes. The toe box in particular has some of the highest pressures and is the best predictor of shoe fit [1,4,14]. For this reason, the evaluation of foot-shoe contact pressure in this paper is focused on the range and specificity of pressure seen in the toe box.

2.2 Sensor Technology

2.2.1 Pressure Sensors

For measuring contact pressure between two surfaces, the standard on the market is a thin-film pressure sensor. These are either capacitive or resistive and are sold primarily in dime-sized pads, palm-sized squares, or thin strips.

Resistive thin-film sensors are the simplest to use and suitable for a wide variety of applications [16]. They fall under the umbrella of force-sensitive resistors (FSRs), which employ the piezo-resistive effect to measure pressure or strain (also called a strain gauge). Piezo-resistivity refers to the property of conductive materials changing electrical resistance when stretched. When pressure is applied to a piezo-resistive material, the fibers stretch to accommodate the shape, thus changing the overall resistance of the material. A typical thin-film FSR displays a linear relationship between force and conductance, and an inverse relationship between force and resistance.

For measuring upper contact pressures between a foot and shoe, there are a handful of studies that used thin-film force-sensitive resistors. In these studies, between 5 and 15 sensors were taped by the researchers to a participant's foot with medical tape and wired to a central board [3,14,15]. This system collected data on the contact pressures at various locations on the foot.

While this process may work well for the limited number of uses required for a study, it would not be ideal for hundreds of trials or for use without a specialist present. It is time-consuming to place and secure each sensor, and it requires in-depth knowledge of the correct placement of each sensor. In addition, the sensors are designed for use on static, flat surfaces. They may not hold up well when bent, rubbed, or twisted, and the sharp edges could become painful for users if a sensor was improperly placed. Lastly, the size and shape of the sensors is limited to what manufacturers currently produce. In the search for more flexible and adaptable FSR sensors, some research is turning to the use of textile sensors.

2.2.2 Textile Sensors

The use of textile electronics, including pressure sensors, is expanding in many fields, from hobby crafting to smart clothing to wearable health monitors. The foundation of many of these textile electronic systems is conductive fabric and thread. There are many types of conductive fabric – some are made with thin strands of metal woven into the composition of the fabric, others use regular threads that have been coated or embedded with conductive elements like carbon, silver, or titanium [17]. These modifications allow the threads and fabrics to conduct electricity and thus can be used to replace or support elements in an electrical system. The primary advantage of using textile electronics is that they are significantly more flexible than regular electrical components, can be adapted to any shape or size, and are easily attached to clothing or other fabric-based articles. For this reason, there are many examples of textile electronics projects in athletic settings.

When it comes to shoes, there is precedent from gait-analysis research [18–23] and from industry for using thin textile pressure sensors in shoes to measure plantar pressure. Danusports and Sensoria are two examples of companies developing socks with embedded plantar sensors for direct-to-consumer sales.

The Sensoria Smart Sock currently on the market was validated in a 2018 study, which determined that it was successful in measuring running cadence through the use of embedded textile sensors in the bottom of the sock [22]. Two additional sock prototypes with textile pressure sensors have been developed and validated for running gait analysis: the "SWEET Sock" and the "DAid Pressure Sock System." The SWEET sock uses piezo-resistive conductive microfiber textiles from Eonyx and has shown to provide reliable pressure measurements [19,23]. The DAid sock also contains embedded sensors on the insole of the sock and was validated successfully against a Pedar insole measurement system [18] – it demonstrated good temporal and pressure sensing capabilities [18,18]. The sensors in the DAid sock are not described in detail but they are textile-based and can be produced using ordinary sock knitting machines [18].

No studies were found that used or proposed using textile sensors to measure the shoe-foot contact forces on the sides or upper part of the foot. Nonetheless, the success of textile pressure sensors embedded in socks and functioning in the foot-shoe environment is promising, and suggests that a data collection system using textile pressure sensors could be successful in measuring upper contact forces in shoes.

3. Design Proposal

In developing the design of a sensor system for textile pressure measurement, the requirements, constraints, and guidelines were distilled from existing literature and interviews with a shoe company. Both a proposed use case and a system design are described below.

3.1 Design Criteria

3.1.1 Customer Needs

The intended user of this sensor system is shoe companies, who would use the system to measure the fit of a shoe. Therefore, the sensors cannot alter how the shoe fits the user, as this would interfere with the system's ability to measure the fit. Moreover, the sensors must be thin, flexible, and have little effect on how the shoe feels to the wearer. For this characteristic, a maximum thickness of 2 mm was chosen, as this is the average thickness of athletic socks. The sensors should have a customizable shape and size so that they can be used in different parts of the foot and for a range of foot sizes.

A shoe company's R&D department provides its own set of design requirements. The sensors should be durable so that they can be used repeatedly and for long periods of time, withstand the bending of putting on and taking off a sock and shoe, and can function within a shoe's environmental conditions (e.g. higher levels of moisture and humidity). The design should be easy and intuitive to use and quick to calibrate so that specialist supervision is not needed. The individual sensors and overall structure should also be able to be cleaned between users for hygienic safety. The system as a whole should allow for multiple sensors to be placed on one foot and should not need to be tethered to a stationary computer for data collection. Given the scale of this investigation, these R&D-specific customer needs were not directly addressed in this paper beyond initial consideration. Further research of this sensor system should include examination of these design requirements.

3.1.2 Precedence in Literature

The exact requirements for range, accuracy, and precision in effective sensors were aggregated from three previous studies: "Ice Hockey Skate Boot Mechanics – Direct Torque and Contact Pressure Measures" (Pearsall 2012) [15], "Medical-Grade Footwear – the Impact of Fit and Comfort "(Hurst 2017)[14], and "Quantifying Fit in Ice Hockey Skate Boots" (Gheorghiu 2005)[3]. These studies all used thin-film force sensitive resistors to measure the pressures between a foot and a shoe.

The amount of pressure felt by sensors around the foot depended on their location and the foot's position. In all three papers, the measured pressures were below 250 kPa. According to Gheorghiu's investigation, highest pressures were found in the toe box, particularly on the 5th metatarsal (smallest toe) (see Figure 1), with pressures ranging 20-120 kPa depending on foot position. Pressures in other locations on the foot ranged from 5 kPa to 80 kPa. These values are supported by the work from Hurst and Pearsall.

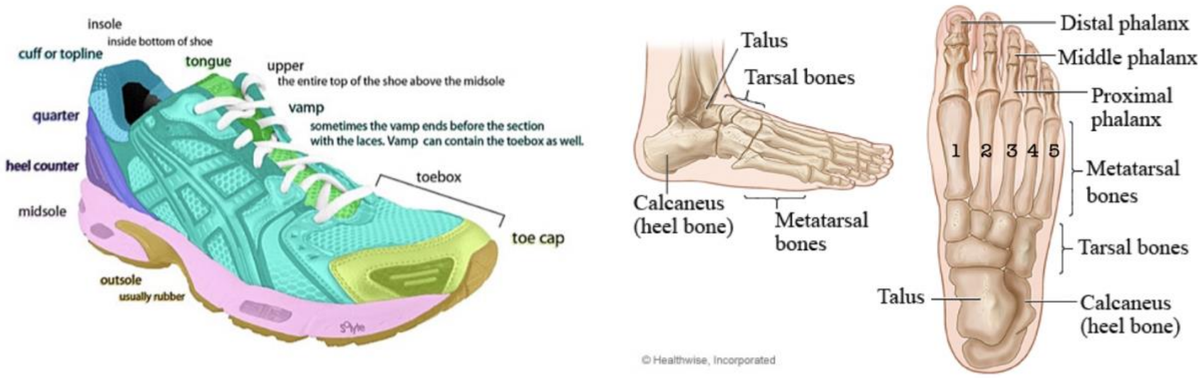


Figure 1: Labeled parts of a shoe [24] (left) and bones of the foot [25] (right)

In Gheorghiu's 2005 work, the 5th metatarsal (small toe) was the only location at which there was a significant difference in measured contact pressures between a small boot (69 kPa), a regular boot (60 kPa), and a large boot (52 kPa). Beyond these papers, it is well supported in shoe-fit literature that the toe box is most influential in determining overall shoe fit. For this reason, the pressures in this region were considered the highest priority for this study (see Figure 2).

3.2 Proposed Use Case

Based on the existing fit-testing process used in shoe companies, as well as the procedure used to measure pressure in the reviewed literature, the following process was proposed:

1. The sensors are placed on the user's foot using a sock-like harness system. Due to this placement, the sensors may experience curved surfaces, stretching, and baseline pressures.
2. Once on the foot, the sensors are zeroed out. This ensures that the unique shape, size, and hardness of the individual foot do not bias the sensor readings.
3. The user puts the shoe on over the sensor system and sits stationary for a few minutes. The readings on the sensors taken at this time reflect the shoe-foot contact pressures when in a static, relaxed position. These are "long-term" pressures.
4. With the shoe still on, the user may then flex their foot, move between different positions, or walk/run with the shoes on. The readings on the sensors taken at these times reflect the shoe-foot contact pressures in varying dynamic positions. These are "short-term" pressures.
5. When finished, the user removes the shoe and the sensors. Together, the long-term and short-term pressure readings quantify the fit of the shoe for that user.

3.3 Evaluation Criteria

For both short-term and long-term pressures, the sensors should show precision, accuracy, and temporal consistency in the necessary range. For precision, the sensors should always display the same voltage when the same force is applied (low variation between sample runs, "*inter*-precision") and should not fluctuate (low standard deviation within a sample, "*intra*-precision"). The sensors should rise quickly to a voltage level and should not drift up or down during the relevant time span. Overall, the resistances measured from the sensors should indicate a clear positive correlation with force applied with a low uncertainty. Lastly, the sensors need to be able to read values in the appropriate range. For this context, the range of highest interest is 20-100 kPa and the sensors need to be able to withstand up to 250 kPa. The testing procedure and data analysis were set up to evaluate the sensors on these design criteria.

3.4 Proposed Design

Based on literature review, twenty locations on the foot were identified for possible sensor placement. The positions shown in Figure 2 were chosen to maximize efficiency of sensors as well as coverage in areas relevant to shoes. The proposed sensor shape is a circle of diameter 7.5mm. This size and geometry fit well on all chosen locations without interfering with the natural curvature of the foot or inducing bending and folding of the sensors.

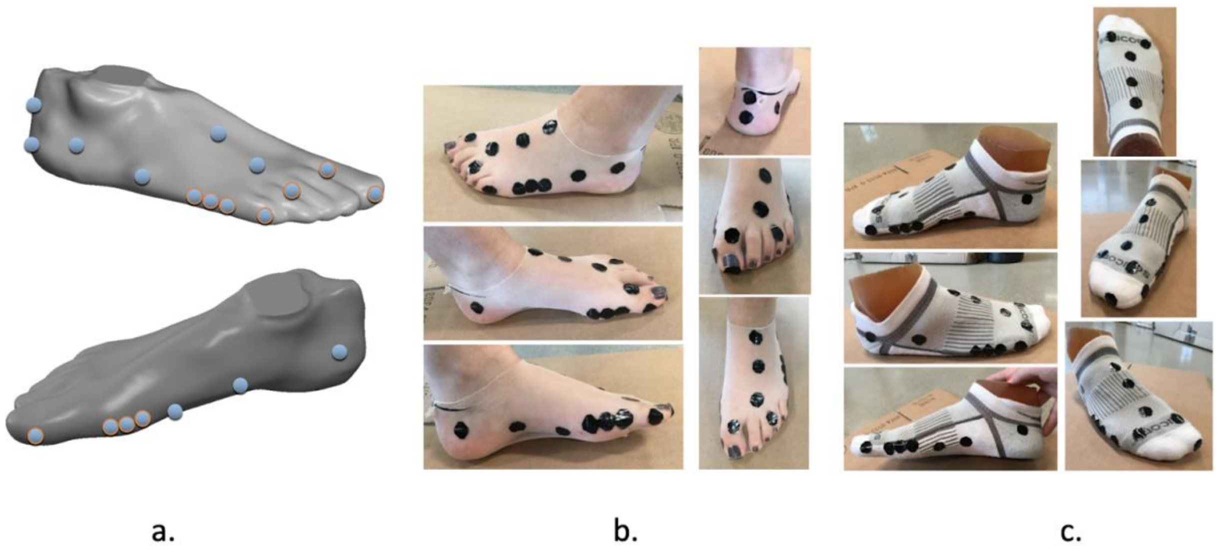


Figure 2: Proposed sensor locations on (a) a virtual 3D foot model, (b) a user foot in women's size US 8, and (c) a rubber cast model of a men's size US 9.5; sensors circled in orange in (a) are in the toebox

The sensors should be connected to streamline electronics, minimize thickness, and provide ease of use. There is precedent in gait-analysis research for embedding pressure sensors on the bottom of socks to measure plantar pressure. For this context, sensors could be sewn onto the outer surface of the sock (directly touching the shoe cavity), the inner surface (directly touching the foot), or sewn into gaps cut in the sock (touching both shoe and sock directly). Another option would be to attach the sensors to a thin fabric sleeve, such as the nylon socks found in shoe stores (see Figure 2), or a fabric harness, and have users wear this either over or under a regular sock. The sensors could also be detachable using thin Velcro or sewn-in pockets so that the sock can be separately machine-washed. This would be a useful design choice if, for example, the sensors experience water damage. Further prototyping and experimentation needs to be done to determine which of these design options is most viable.

For the electronics, an Arduino Flora [26] is proposed because it is intended for textile electronic projects with electrical ports designed for thread attachment. Conductive thread and metal snaps could be used to connect the textile sensors and a LiPo battery to the Flora. Note that the route of the threads should be carefully planned across the foot to minimize damage or interference; a coating or other protection might be necessary to ensure a good connection. Lastly, the Arduino Bluetooth module [27] designed to work with the Flora could be used to transmit data from the sock to a computer (Figure 3).

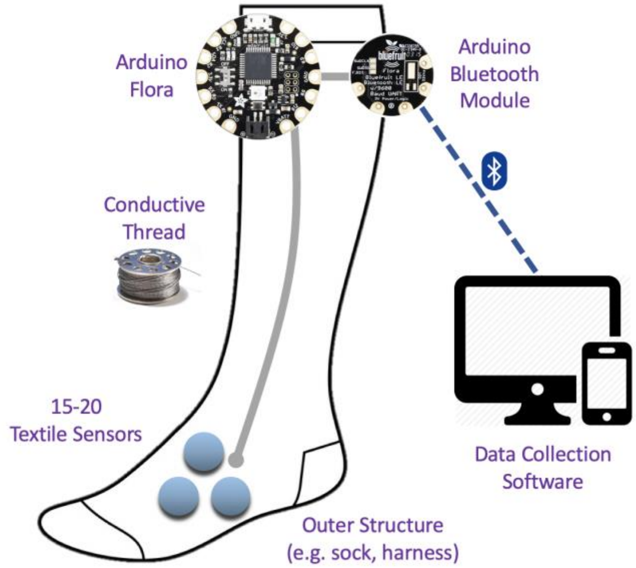


Figure 3: Proposed system design

4. Experimental Setup

4.1 Sensor Prototype Fabrication

This experiment was conducted with four hand-made textile pressure sensors. Each sensor has a 3-by-3 square inch contact surface with two protruding tabs for wiring attachment. The sensors are 0.75 mm thick when not compressed.

4.1.1 Design Choice

The sensors were built following the instructions of Francisco Pizarro in his 2018 paper, "Easy-to-Build Textile Pressure Sensor" [28] (see Figure 4). This design consists of three layers: two sheets of conductive fabric sandwiching a layer of piezo-resistive material. This design was chosen as it fulfills requirements for flexibility and thickness, allows for rapid prototyping of different materials, and is cited in literature as an effective way to design this type of sensor [28–31]. The prototypes were built following the size and shape of Pizarro's sensors, however, further modification would be necessary to fit the sensor system proposed in section 3.4.

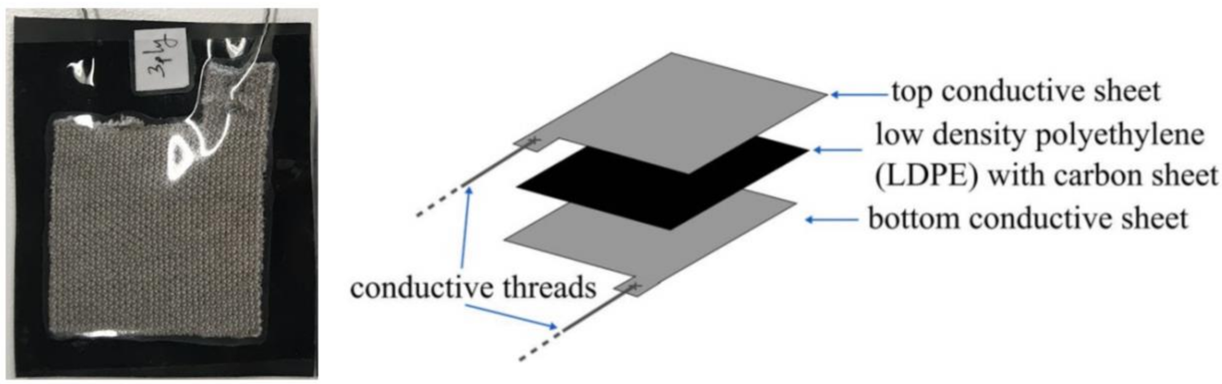


Figure 4: (left) an example of a sensor prototype built for this project following F. Pizarro's design and laminated in clear packing tape and (right) the design schematic for a resistive textile pressure sensor from F. Pizarro

4.1.2. Material Choice

Two versions of conductive fabric were chosen: a knit jersey conductive fabric from Adafruit [32], and a silver fiber conductive stretch fabric from Amradield [33] (Figure 5). These materials were chosen for their conductivity, flexibility, and thickness. A third material was initially investigated but discarded early in the testing sequence because it was not viable in this experimental setup [34]. A pressure-sensitive conductive sheet from Adafruit (similar to Velostat or Linqstat) was chosen as the piezo-resistive material, due to its thickness of 0.1mm, bendability, and performance in pressure sensors in existing literature [29–31,35]. Two types of conductive thread were used to connect the conductive fabric to the circuit: 2 ply and 3 ply conductive thread from Adafruit [36,37] (see Figure 5). Both are made with 100% 316L stainless steel and have a low resistivity: 16 ohms/ft and 10 ohms/ft respectively.

For each fabric type, two sensors were made, one with each weight of thread for a total of four sensors (see Table 1). The thread was knotted into the upper tab of the conductive material on each side, as shown in Figure 4, and was stitched in an X shape over the tab to ensure multiple connection points.

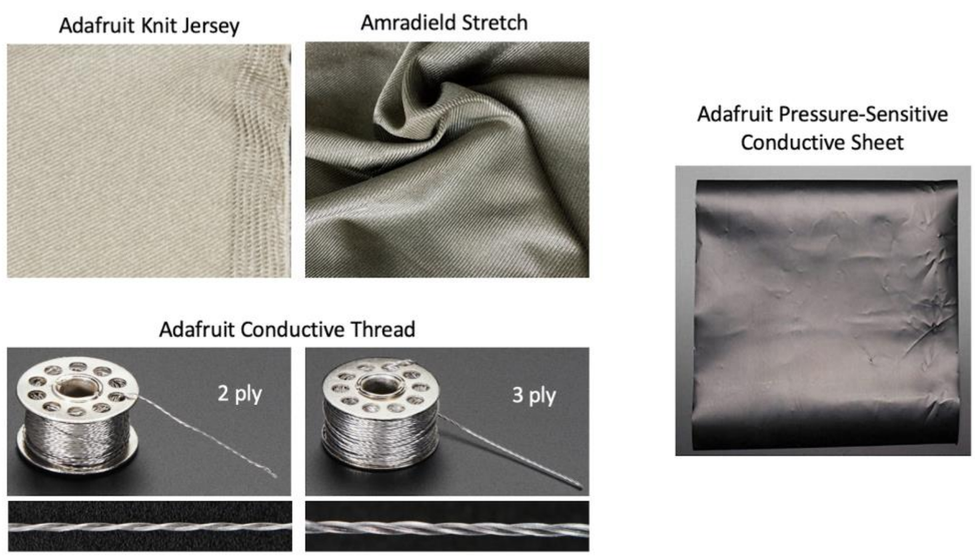


Figure 5: Materials used for sensor prototypes; conductive fabrics (left above), conductive threads (left below), piezo-resistive sheet (right)

Sensor	Fabric	Thread	Baseline Resistance	Fixed Resistor Used in Circuit
1	Adafruit Knit Jersey	2 ply	20 kΩ	15 kΩ
2	Adafruit Knit Jersey	3 ply	14 kΩ	15 kΩ
3	Amradield Stretch	3 ply	160 Ω	121 Ω
4	Amradield Stretch	2 ply	300 Ω	332 Ω

Table 1: Textile pressure sensor prototypes

4.2 Testing Setup

Sensors were tested with six different weights corresponding to the types of pressures typically seen around the toe box, the area most important in determining fit (see Figure 2). These weights were chosen to represent both the typical range and specificity needed to distinguish different levels of pressure at the toe, and also to withstand the highest likely pressures that might be seen while in use in this context. The critical characteristic wanted from the sensors is if they display the same amount of voltage difference for the same weight each time – standardized measuring weights were used so that the weight on the sensor was the same each time. The weights were chosen as the closest block amount to the desired pressure (see Table 2).

Goal Pressure based on literature	Goal Force on testing block	Goal Mass on testing block	Standardized Weight Chosen for Experiment
kPa	*N*	*g*	*g*
20	1.61	164	150
40	3.24	331	300
60	4.86	496	500
80	6.48	661	650
100	8.1	830	850
350	28.3	2890	2980

Table 2: Translation of goal pressures (left) into standardized weights available for lab testing (right), based on a contact surface area of 0.81 cm^2

To further control the pressures felt by each sensor, a testing block was placed between the sensor and the standardized weight so that the surface area of the pressure was constant. The block was an aluminum cube with a surface area of 0.81 cm^2. This size fit easily in the center of each sensor so that edge conditions are not affecting the sensor readings, and also corresponds to the approximate size of sensor that would be used on a foot, as determined above from a literature review [3,14,15].

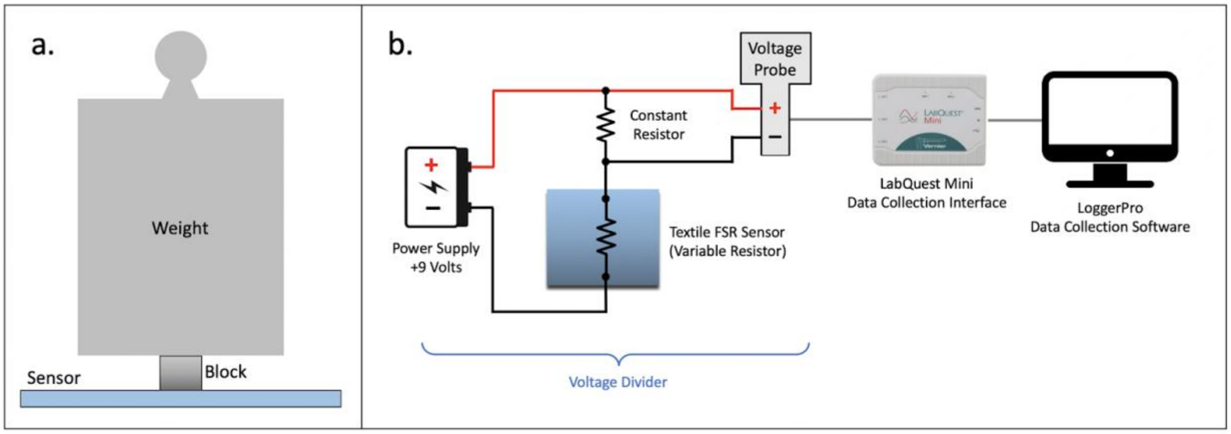


Figure 6: Testing setup (a) side view of the weights sitting on the sensor, and (b) schematic of the circuit used to collect data, where the implementation of a voltage divider allows for a voltage probe to be used to measure changes in resistance of the textile sensor prototype

4.3 Data Collection

To read and record the data from the sensors, a voltage divider and voltage probes were used, as shown in Figure 6. Metal crimps were attached to the conductive threads of each sensor to prevent damage from repeated connection and disconnection of alligator clips. For each sensor, the static resistance was measured and a fixed resistor in the same range was chosen for the constant resistor in the circuit. These resistances are as follows: a 15 kΩ resistor was used for sensors 1 and 2, with static resistances of 20-30 kΩ and 12-14 kΩ respectively; a 121 kΩ resistor was used for sensor 3 with static resistance of 160-180 Ω, and a 332 Ω resistor was used for sensor 4 with static resistance of 270-320 Ω (Table 1). The equivalent resistance of the sensor can be calculated from the voltage probe output as follows:

$$R_{Sensor} = R_{Fixed}(9 - V)$$

Equation 1: Equation for resistance of the resistor R based on the fixed resistor (R_{Fixed}) and the voltage probe output V

The procedure was designed to test the sensors on long-term and short-term constant force application. For the long-term force application, weights were set onto the sensor for 45 seconds and then removed for 45 seconds. This was repeated five times for each sensor with each weight. The length of 45 seconds was chosen after establishing that the sensor readings stabilized within 30 seconds and thus the relevant information could be captured in this timespan. For the short-term force application, weights were set onto the sensor for 10 seconds at a time and then removed for 10 seconds; this was repeated 10 times in direct succession. For both long-term and short-term tests, the sensors were taped to the table to minimize lateral movement, and the voltage reading was zeroed out after placing the testing block onto the sensor.

Data was collected using a LabQuest Mini and Logger Pro software.

4.4 Data Processing

The data points collected in the first 0.3 seconds were averaged to find the baseline starting value. All data was adjusted to account for any offset from the intended input of zero in this baseline value. The voltage probe exhibited a step response in reaction to the placement of a weight on the sensor. The data points collected during the time that the weight was on the sensor were identified as the “high” values for that sample run. Once the weight was removed, the voltage probe exhibited a further step response to return to a baseline value. The data points collected during the time after the weight had been removed were identified as the "low" values for the sample run. Note that the large fluctuations sometimes present at the beginning of the "high" region of the sample were due to the repositioning of the weight on the sensor (human intervention) and are thus not reflective of the sensor response. For the long-term experiments, there was one "high" region and one "low" region per sample run. For the short-term experiments, there were ten "high" regions and ten "low" regions. Figure 7 shows the voltage probe data for one sample run of the long-term and short-term pressure experiments.

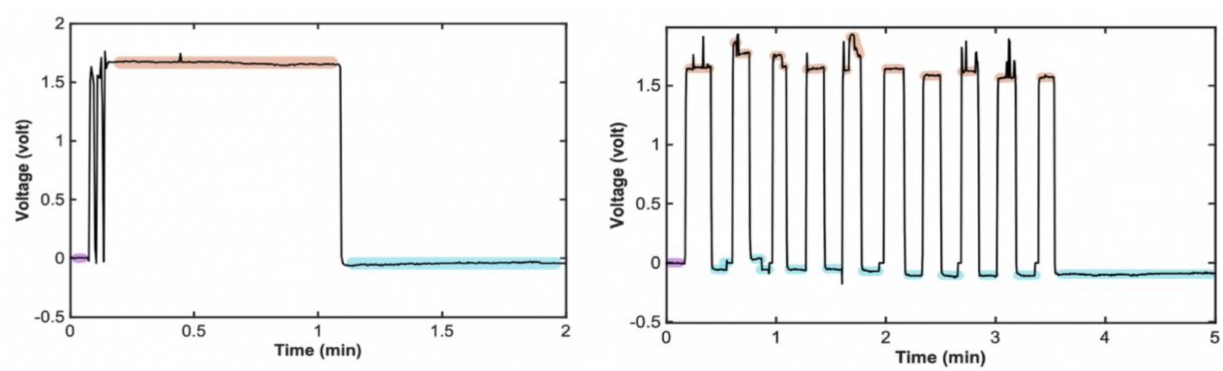


Figure 7: Voltage output for Sensor 4 for (left) sample run 3 with 650g long-term applied force, and (right) sample runs 1-10 for 500g short-term applied force. Data highlighted in purple were used to calculate the pre-weight baseline. Data highlighted in orange were identified as "highs," and data highlighted in blue were identified as "lows."

For each sample run, the average and standard deviation of each "high" region (one for long-term, ten for short-term) and low "region" was calculated, as seen in Figure 8. This standard deviation represents the amount of fluctuation in the sensor output within one "high" region. A well-performing sensor would have low amounts of fluctuation within each "high" region – when a constant force is applied to the sensor, the output is stable and without noise.

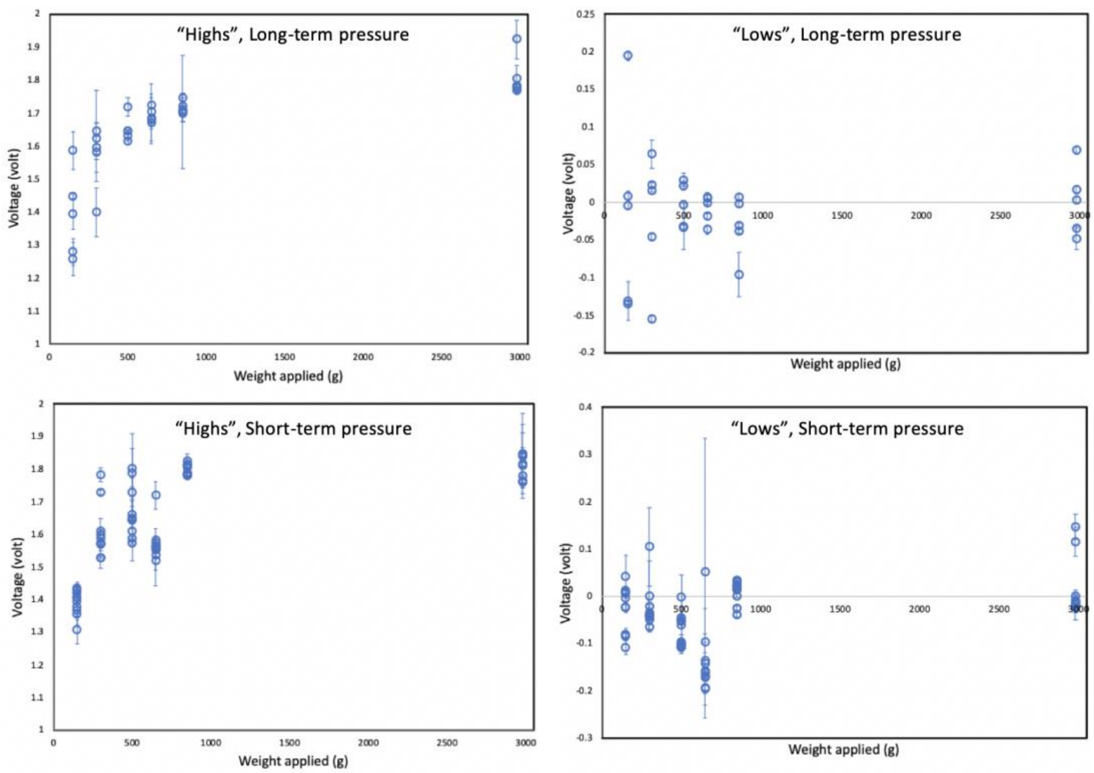


Figure 8: Average highs and lows for sensor 4 with long-term and short-term applied force; shown with error bars of standard deviation

The sensors were tested with 6 weights, ranging from 150g to 2980g. For each weight, multiple samples were taken to evaluate the repeatability of the sensor. The "high" and "low" averages shown in Figure 8 were averaged across all samples for a particular weight and sensor. This is the overall average voltage value that the sensor outputs for each weight. The 95% uncertainty was calculated for each value and included both the intra-sample standard deviation, as in Figure 8, as well as the inter-sample standard deviation, representing the variation between samples for a particular weight. A well-performing sensor would have a small amount of variation between sample run average "highs" – when a constant force is applied to a sensor multiple separate times, the average output each time will be approximately the same.

Analysis was completed in MATLAB and Microsoft Excel.

5. Results

When force was applied, sensors 3 and 4 showed better precision than sensors 1 and 2, but overall sensor 3 had the best accuracy for converting resistance to force (Figure 9). All four sensors demonstrated appropriate range and temporal consistency for this application.

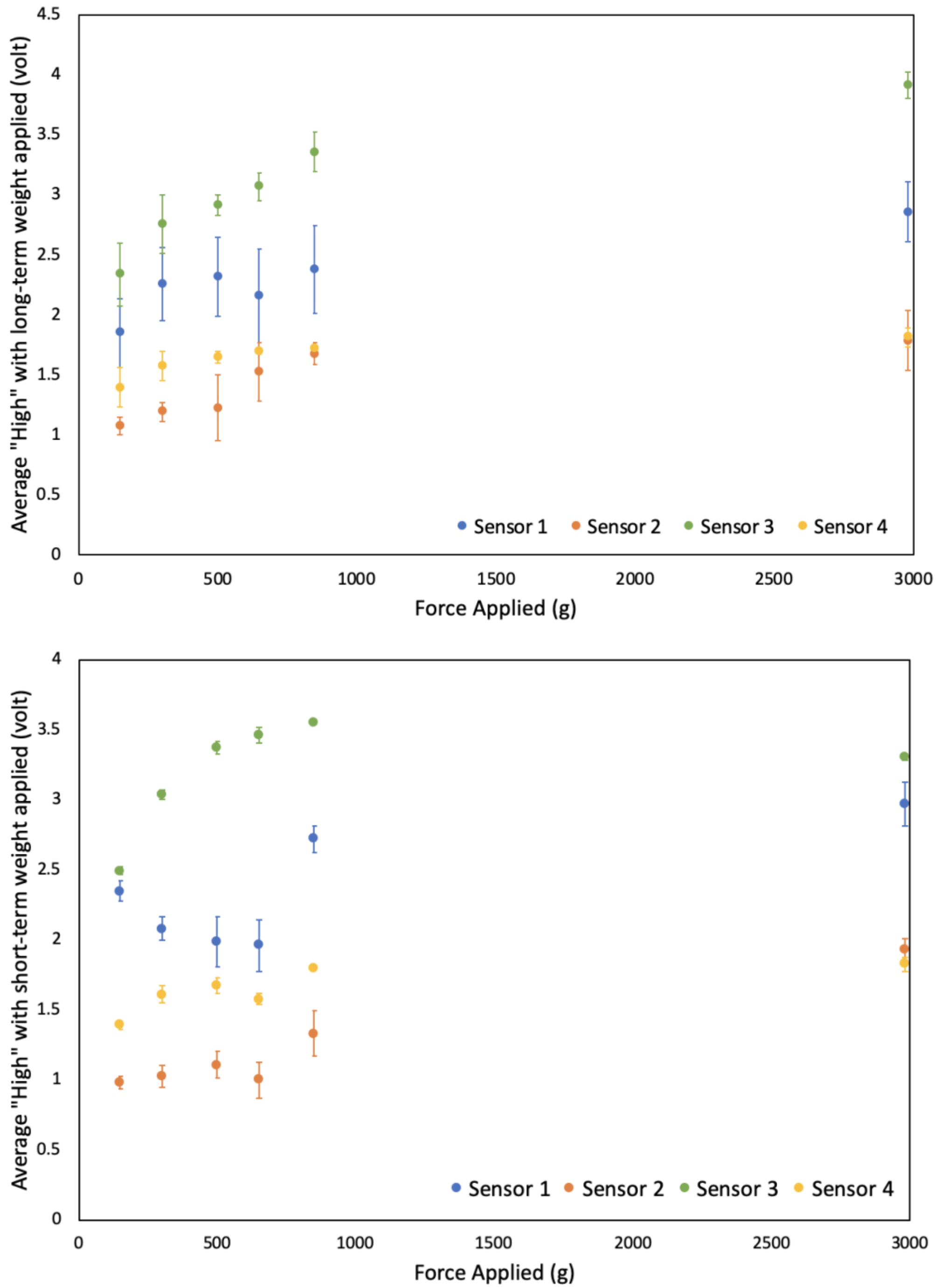
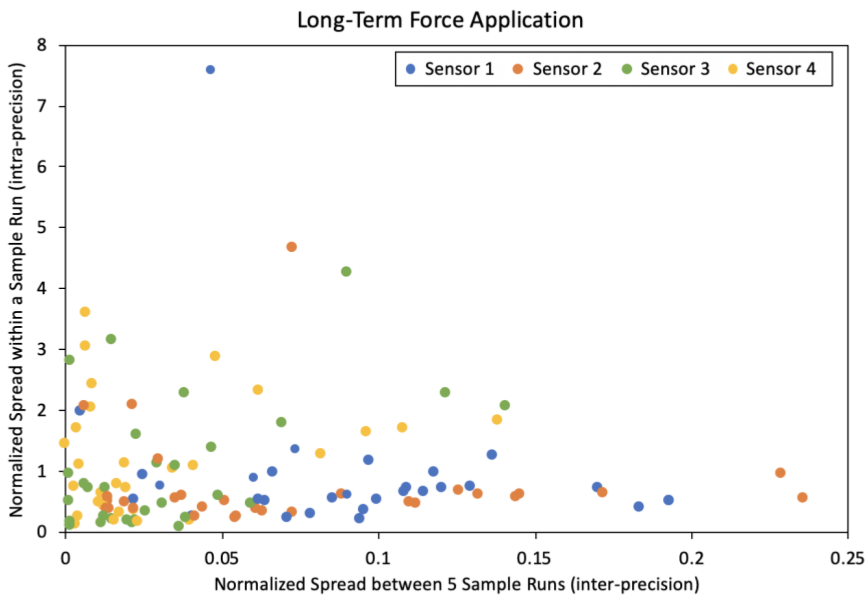


Figure 9: Overall average "high" outputs at each applied force, shown for all sensors with long-term applied force (above) and short-term applied force (below); error bars represent 95% uncertainty. With the exception of sensor 1 with short-term pressure application, all sensors displayed a clear positive relationship between input force applied and output voltage.

5.1 Precision

The precision of the sensors is two-fold: sensors should always display the same voltage when the same force is applied (*inter*-sample precision - low variation between sample runs) and should not fluctuate at this voltage level (*intra*-sample precision - low standard deviation within a sample). Figure 10 shows the comparison of all four sensors along both measures. A well-performing sensor would have data points clustered in the bottom left corner – low variation within each sample and between samples for each weight. Sensors 3 and 4 performed similarly, while sensors 1 and 2 performed similarly. For the long-term pressure tests, sensors 1 and 2 have better intra-sample precision than sensors 3 and 4, but have worse inter-sample precision. In the proposed use case, inter-sample precision is more important because the values would likely be averaged over time for each sample run. It is better for a sensor to output the same average value each time a constant weight is added, even if there is a lot of fluctuation within each sample, then for a sensor to output a stable stream of values but have a large variation in the average value outputted each time a constant weight is added. It was found that sensor 3 had better inter- and intra- precision in short-term pressure tests.



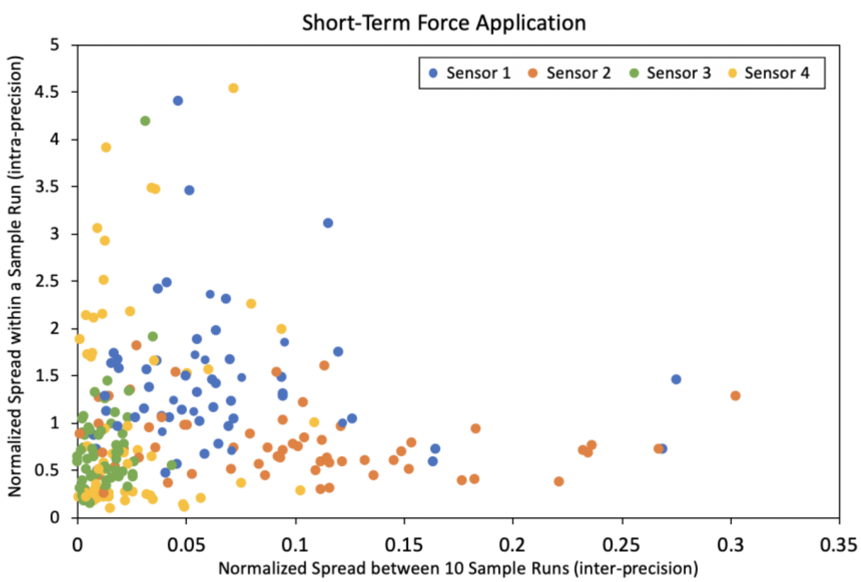


Figure 10: Inter- and Intra-precision for all sensors at all forces; long-term force application (above) and short-term force application (below). A well-performing sensor would have low inter- and intra-precision. Sensor 3 at short-term force application performs best on both criteria. Sensors 3 and 4 have better inter-precision but sensors 1 and 2 have better intra-precision.

It is also important that sensors return to a value close to the pre-weight baseline after the weight is removed. The average low values for each sensor at each weight level were characterized as the “lows” (Figure 11). A well-performing sensor would have values clustered closely around zero with small uncertainties. For long-term pressures, there were no statistical differences between sensors for the average “low”, but sensor 1 had statistically higher uncertainties than sensors 1, 2, and 3. For short-term pressures, sensor 1 had statistically different average “lows” and uncertainties than sensors 1, 2, and 3. Sensor 1 is the only sensor that showed a statistical difference between long-term and short-term pressure “lows.”

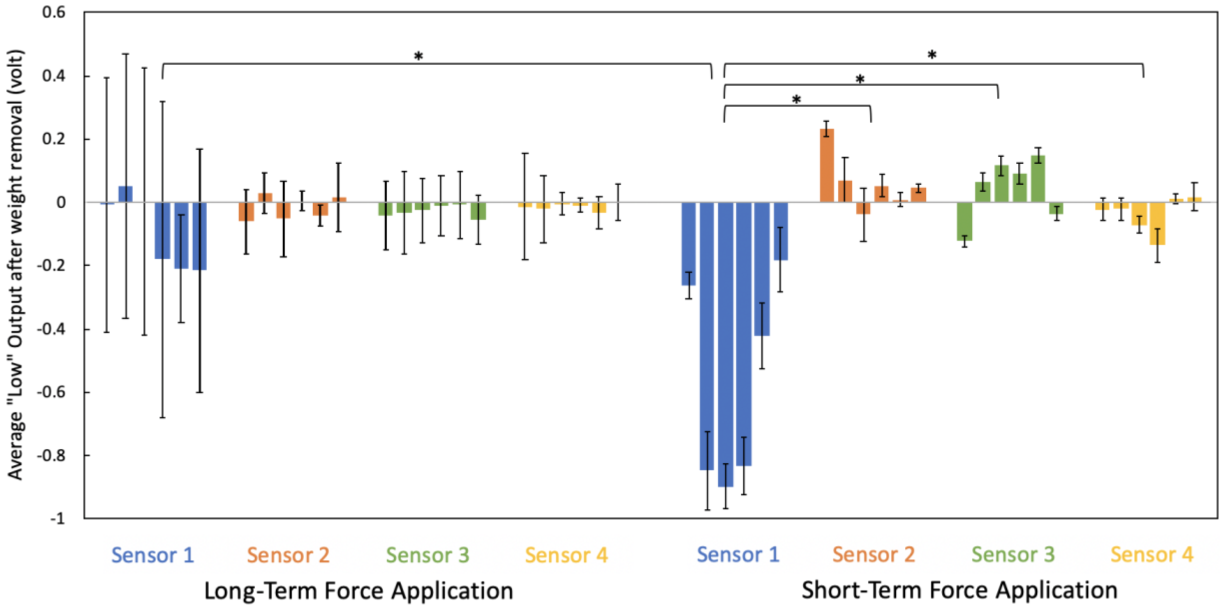


*Figure 11: Average "low" output from sensors after weight is removed, shown with error bars of 95% uncertainty; * p<0.05. Sensor 1 performs substantially worse than sensors 2-4, with “low” values furthest from zero and the largest uncertainties. There is no statistically significant difference in the return-to-zero performance of sensors 2, 3, and 4.*

5.2 Accuracy

All sensors displayed a positive correlation and inverse relationship between resistance and applied force. This is in line with typical thin-film FRS pressure sensors [38]. All sets of data were fit with an inverse curve of the form $y = \frac{A}{x} + B$, as seen in Table 3 and Figures 12 and 13.

Data Set		Parameter A (10^{-3})	Parameter B (10^{-1})
		Curve Fit $y = \frac{A}{x} + B$	
Sensor 1	Long-Term	6.0 ± 2.6	9.5 ± 0.26
	Short-Term	2.9 ± 2.6	9.8 ± 0.26
Sensor 2	Long-Term	4.7 ± 1.6	9.6 ± 0.16
	Short-Term	4.3 ± 1.6	9.7 ± 0.16
Sensor 3	Long-Term	11.9 ± 2.7	9.1 ± 0.26
	Short-Term	9.2 ± 1.0	9.3 ± 0.10
Sensor 4	Long-Term	2.84 ± 0.59	9.8 ± 0.06
	Short-Term	2.9 ± 0.51	9.8 ± 0.05

Table 3: Parameters for Inverse Curve Fit, shown with 95% uncertainty. Parameter B is between 0.91 and 0.98 for all sensors and pressure tests. Parameter A varies from 2.9e-3 (sensor 1 short-term and sensor 4 short-term) to 11.9e-3 (sensor 3 long-term).

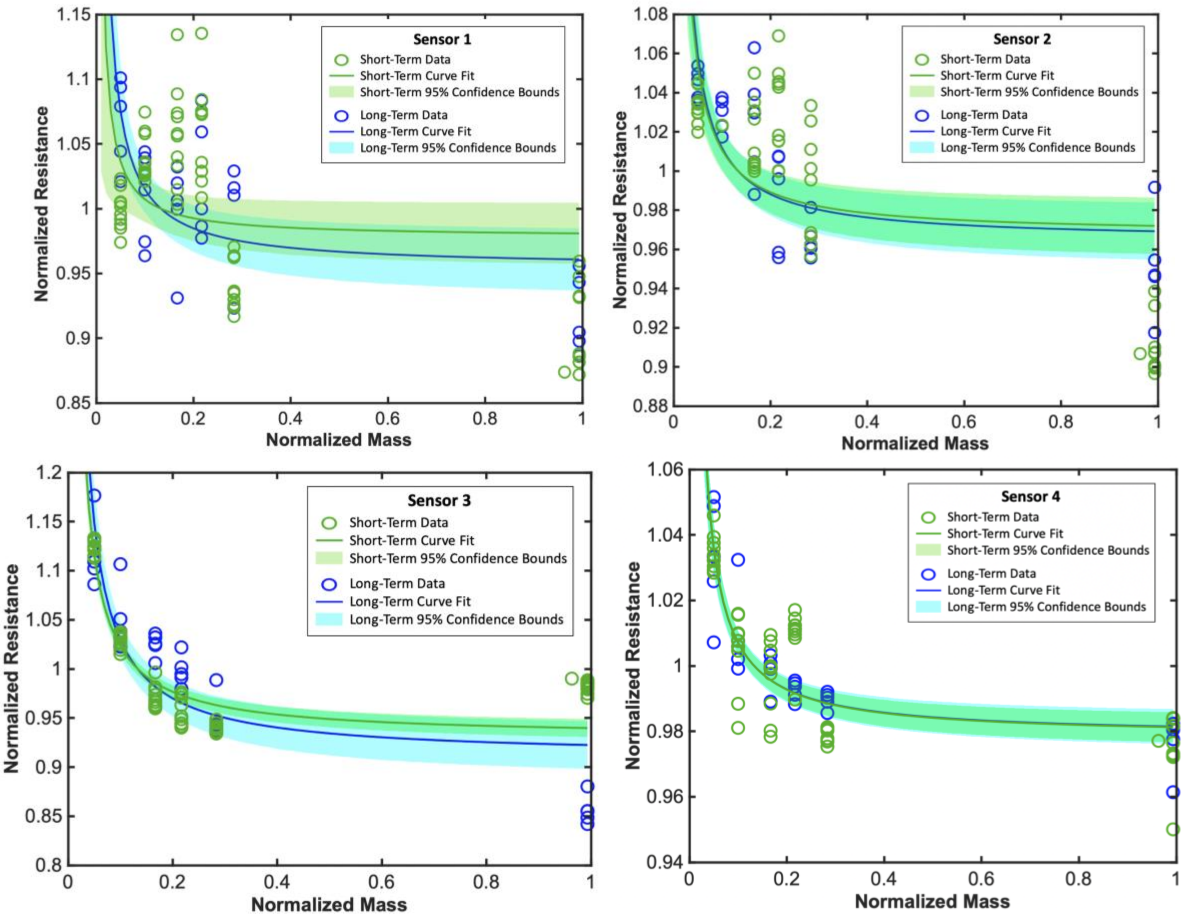


Figure 12: Force-Resistance data sets for short-term (green) and long-term (blue) force application, sorted by sensor, each plotted with an inverse curve fit and 95% confidence bounds. Sensor 4 demonstrates the best agreement between data sets of short-term and long-term pressure tests and also has the tightest 95% confidence bounds.

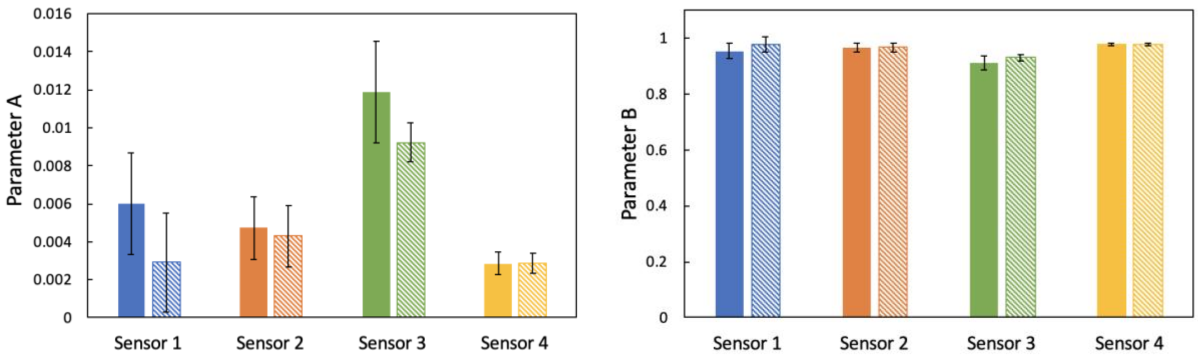


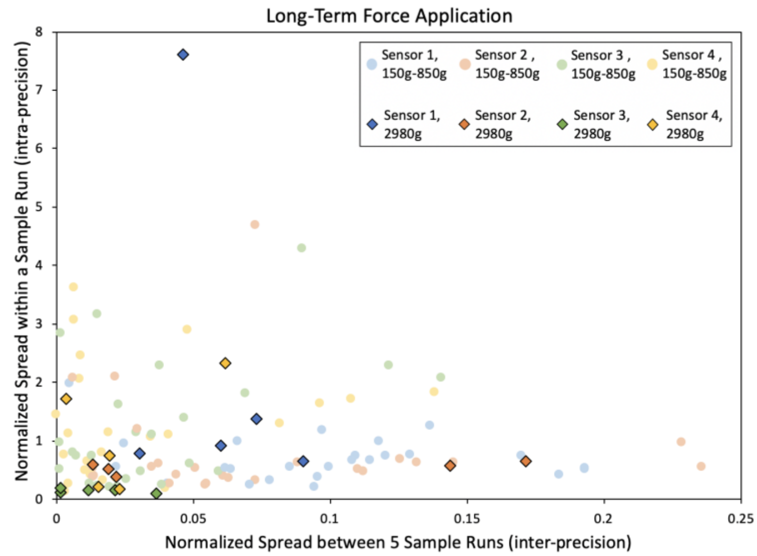
Figure 13: Parameters for Inverse Curve Fit, shown with error bars of 95% uncertainty. Sensor 3 has the highest values for parameter A, for both short-term and long-term pressure tests, meaning it demonstrates the most sensitivity to changes in force. Sensors 2, 3, and 4 had statistically negligible differences in parameter A values between short-term and long-term pressure tests. For parameter B, there was no statistical difference between any of the eight data sets.

Because *B* is approximately 1 for all data sets, the *A* parameter can be used as the indicator for sensitivity. A higher *A* for a sensor will yield increased resistance sensitivity to changes in applied force. This is important in a shoe-fit context because changes in force levels may be small and a sensor needs to distinguish between them. Sensor 3 had the highest sensitivity for both long-term and short-term force applications. Sensors 1 and 2 had approximately half the sensitivity as sensor 3, and sensor 4 had the lowest sensitivity (see Figure 13).

It is also valuable for a sensor to show the same sensitivity for both short-term and long-term force applications. Sensors 2, 3, and 4 had a negligible difference in parameter *A* between short and long forces.

5.3 Range

The sensors need to show reasonable data for values in the entire range. Figure 14 below demonstrates that all four sensors show similar precision scores at the max value of 2980g as compared to at the lower weights for that sensor. The same is true for the values that sensors return to after weight is removed (see Figure 15).



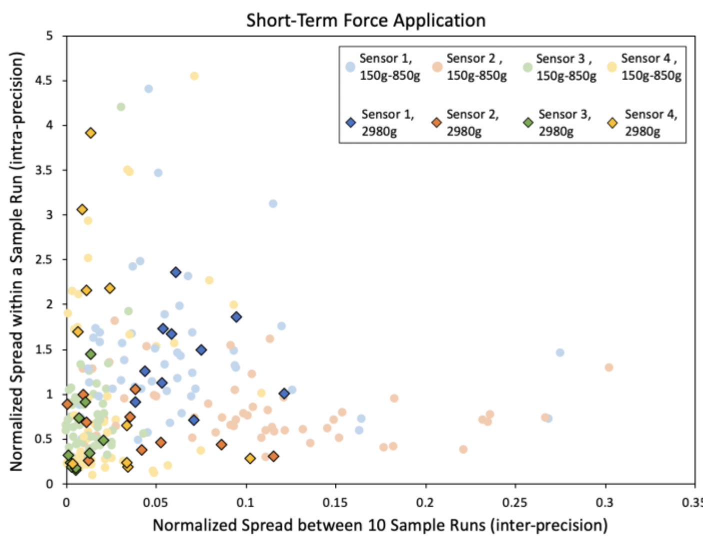


Figure 14: Inter- and Intra-precision for all sensors at all forces, with data points for max force of 2980g bolded for emphasis. For both long-term force application (above) and short-term force application (below), the precision of output data from 2980g force tests was not significantly different than the precision at lower force applications; all four sensors perform with approximately the same precision at high force as at low force applications.

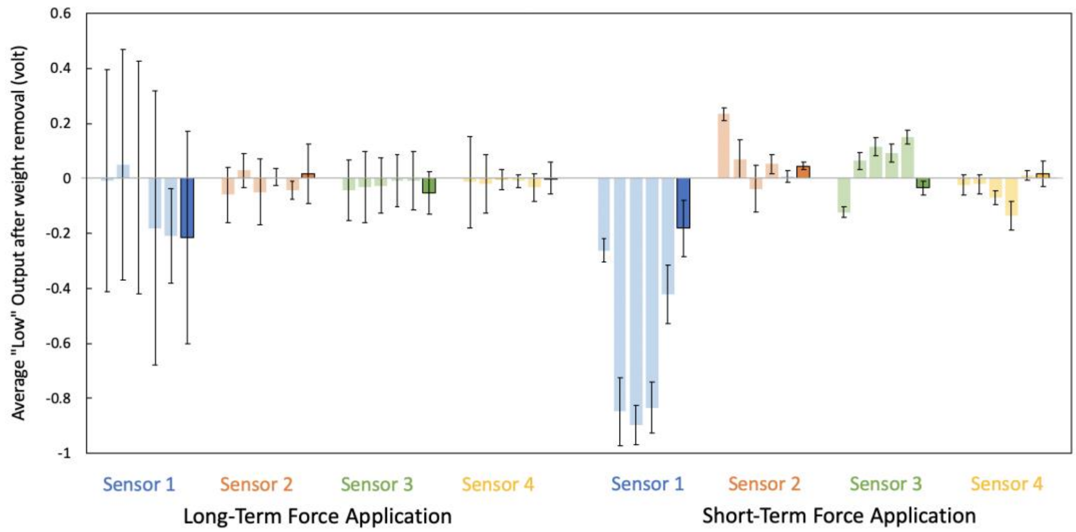


Figure 15:Average "low" output from sensors after weight is removed, shown with error bars of 95% uncertainty; data points for 2980g bolded for emphasis. Neither the distance from zero nor the amount of uncertainty is significantly different for the sensors after the removal of 2980g as compared to after the removal of lower forces. All four sensors perform with approximately the same precision when returning to a baseline "low," regardless of force application.

For sensors 1 and 2, the outputs for 2980g short-term applied force significantly altered the curve fit, indicating that the outputs at high forces are not consistent with the outputs from a lower range of forces. However, the curve fit for sensors 3 and 4 at short-term application, as well as for all sensors at long-term application, did not change significantly when outputs from 2980g force were included or excluded. Thus, sensors 3 and 4 demonstrated a consistent force-resistance relationship across the entire range of measured forces.

By nature of the inverse relationship, all sensors will display lower sensitivity at higher forces. However, the range of best sensitivity for a sensor can be adjusted by changing the driving voltage and the fixed resistor in the circuit.

5.4 Temporal Consistency

In order to be viable for the shoe-fit design context, sensors should rise quickly to a voltage level for an added force and should not drift up or down during constant force application. The same should be true when a force is removed. This is important so that users can collect valuable data without having to worry about getting the data in a specific time frame (after it has settled, before it drifts) and also so that it can take accurate measurements for short-term force application.

All four sensors demonstrated good temporal consistency in rising quickly to a constant voltage after force is applied. For both short-term and long-term force application, sensors reached a steady "high" voltage value within 1.2 seconds of force application.

The relationship of voltage to time was linear for all sensors after weight was applied. Sensor 3 showed the most drift of voltage over time with weight, with highest slopes for 150g and lowest slopes for 2980g force (see Figure 16). At most, this slope accounted for a drift of 10% in one minute with respect to the average value, yet showed the least drift for 2980g, with 0.1-0.5% drift in one minute. This is a negligible change for the time frames tested. By inspection, the slopes for sensors 1, 2, and 4, are smaller than the slopes for Sensor 3 at 2980g and thus are negligible as well – statistically insignificant or accounting for less than 0.5% change over one minute.

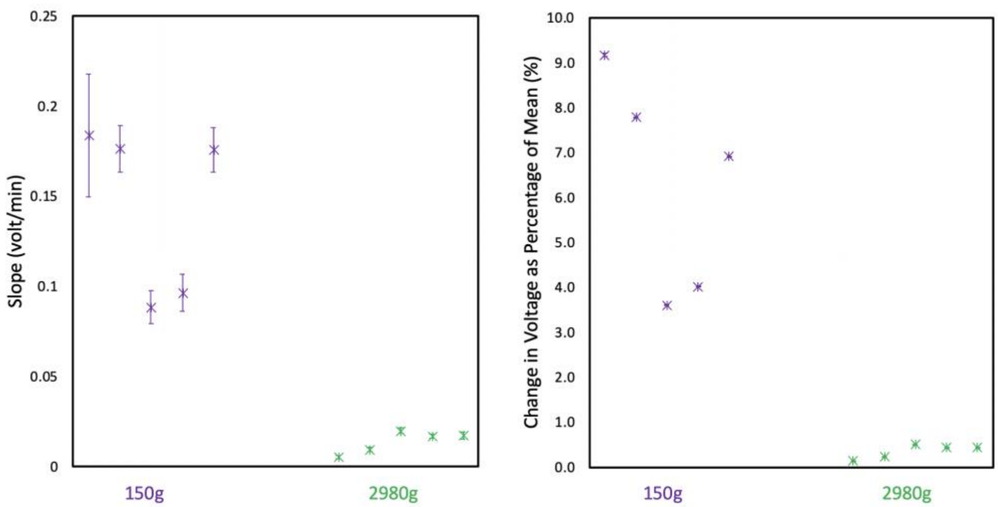


Figure 16: Data for Sensor 3 with long-term force application of 150g and 2980g; slope of linear fit for "highs" (left) and change in "high" voltage over a minute as a percentage of the mean voltage (right). Out of all four sensors, sensor 3 displayed the most drift of voltage over time with weight applied; the highest slopes were with 150g applied force and resulted in upwards of 10% change in voltage over one minute. Sensor 3 had the lowest drift with a force application of 2980g, with slopes under 0.05 volt/min and accounting for under 1% change in voltage per minute. All other sensors performed as well as or better than sensor 3 at 2980g applied force.

After the force was removed, sensors 2, 3, and 4 returned to a stable "low" value within 2 seconds, while sensor 1 took upwards of 18 seconds (for 850g) but typically stabilized in 2-10 seconds.

None of the sensors showed significant drift over time for "low" values. Voltage was either linear with time with a negligible slope, or approached a constant value asymptotically.

6. Conclusions

6.1 Recommendations for Design Embodiment

Overall, the sensors made with Amradield Stretch fabric (3 and 4) performed better in precision, accuracy, and range than those made with Adafruit Knit Jersey (1 and 2). Amradield Stretch is therefore recommended as the fabric to investigate further for textile pressure sensors in this design. The construction design of the sensor prototypes was effective for rapid prototyping and satisfied the basic design requirements for thickness, flexibility, and baseline functionality as a pressure sensor. No significant difference in sensor performance was found between the two thread types (Adafruit 2 ply and 3 ply).

Sensors 3 and 4 performed better than sensors 1 and 2 in precision by a factor of two. When a force between 1.61 N and 28.3 N (150-2980g, 20-350 kPa) was applied, sensors 3 and 4 outputted a signal that was low in noise and almost twice as consistent across repetitions than sensors 1 and 2. All sensors had low levels of noise in the signal (intra-precision) for both short-term and long-term pressures. This is valuable because it would allow a research to easily, reliably, and quickly extract pressure information from the sensor signal. All sensors displayed approximately the same output each time for each particular force application (inter-precision). This means that if a user tried on the same shoe multiple times, the sensor outputs would be consistent.

A successful sensor needs to be both precise and accurate. All sensors displayed a positive correlation and inverse relationship between resistance and applied force. This is in line with common non-textile thin-film FSR pressure sensors; therefore, both the fabrics and the design of the prototypes show promise. Of the four prototypes, sensor 3 showed the most output sensitivity to applied forces – twice as much as sensors 1 and 2 and three times as much as sensor 4 – meaning it would be more successful in differentiating between small variations in force. Due to its high level of sensitivity, this would make it the most accurate of the four sensor prototypes.

For both precision and accuracy, sensors made with Amradield Stretch fabric performed, on average, twice as well as those made with Adafruit Knit Jersey. It is suggested that future sensor prototypes be made with Amradield Stretch, as this is more likely to provide pressure measurements that are correct and usable.

All four prototypes demonstrated adequate range and temporal consistency within the parameters of the tests. The sensors registered reasonable outputs for pressures expected in shoe-foot contact – 20 to 350 kP – and did not display significantly different levels of accuracy or precision at extreme pressures. The measurements were stable over time with no significant drift or change in noise level for up to 1 minute of constant force application.

Results did not indicate any significant difference between prototypes with 2 ply conductive thread (sensors 1 and 4) and those with 3 ply conductive thread (sensors 2 and 3).

6.2 Considerations for Further Investigation

Though the sensor prototypes satisfied basic requirements for functionality, further work is needed to fully quantify their capability. This includes testing for temporal consistency over longer periods of time (e.g. an hour), output accuracy and precision with shorter force applications (e.g. impulse inputs), and output accuracy for pressures differentials smaller than 10 kPa.

The sensor design used for the four prototypes shows promise but could be optimized. Further research is needed to compare performance with other textile pressure sensor designs. Future work should also include investigation of all elements in the overall system design, such as the Arduino connection, wiring pathways, and the method for attaching sensors to socks. Both the sensors and the system design should be evaluated for durability and washability, as well as failure analysis regarding minimum repetitions to failure.

Lastly, once a full-system prototype is available for textile pressure measurement in shoes, it should be validated against existing literature that use plastic thin-film sensors for shoe-foot contact pressure measurement.

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