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DESIGN OF A CUSTOM SENSING AND ACTUATING CUSHION FOR USE IN PRESSURE RELIEF IN WHEELCHAIR USERS

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ABSTRACT

Pressure sores impact a wide range of individuals including wheelchair users. Solutions to address pressure sore prevention are limited. This work is aimed at developing devices to prevent pressure sores in wheelchair users with limited mobility or sensation. Informed by stakeholder input, we present a dynamic cushion design to sense areas of high pressure and actuate to relieve that pressure. We experimented using resistive sensors in a grid formation to map pressure across the seat. To relieve pressure, we propose a grid of custom pneumatic bladders to inflate in response to sensor thresholds. Bladders will inflate to redistribute pressure. After experimenting with a variety of possible bladder geometries, we selected torus-shaped actuators to optimize durability, stability, and increase breathability in the final design. Given the ability to fabricate custom bladders and program controls, the proposed device can be tailored to users' specific needs. While static cushion solutions exist on the market, our custom design allows users to dynamically alleviate pressure eliminated the need to constantly readjust position and ultimately reduce time spent treating sores.

Keywords: wheelchair, pressure sores, sensors, pneumatics

1. INTRODUCTION

Pressure sores are a prevalent problem in individuals with limited mobility [1]. It is estimated that per year, approximately 3 million people are diagnosed with a pressure ulcer, and over 500,000 of these patients need extended hospital stays for treatment [2]. There are over 100 risk factors associated with disease, including low body mass index, limited mobility, and prolonged seated positions [3]. Individuals who use wheelchairs are prone to pressure ulcers for these reasons. Wheelchair cushions are designed to relieve mechanical stress and pressure from the body; however, static designs limit the ability for cushions to adapt to user needs as pressure sores develop.

Commercially available passive wheelchair cushions aim to relieve localized pressure on the seated surface with a wide variety of materials [4]. The two most common designs are inflatable bladders and gels, commonly oriented in a grid. Available models differ from each other based on the size, quantity, and placement of the cells. Air filled bladder designs are comprised of cells that can be inflated and deflated by the user. Common gel-based cushions include ventilation holes to provide a cooling effect and a soft fabric cover to increase comfort for the user. Although inflatable cells and gels are widely available and can relieve pressure, they lack the ability to sense and respond to changing pressures. Dynamic and adaptive cushions are necessary to detect early causes of pressure sores to improve outcomes for individuals who use wheelchairs.

Technologies are under development to address prevention and treatment of pressure ulcers specific to wheelchair users [5]. To address sensing across the seat cushion, Ahmad et al developed a cushion that embodies a sheet-like sensor that can detect pressure in different seating positions [6]. A conductive fabric-based sensor solution uses cushion pressures to detect posture positions to communicate to the user [7]. In addition to sensing, actuation has been explored to relieve seated pressures. Carrigan et al included pneumatic actuation in a seat cushion design to enable development of a dynamic system for pressure regulation in power wheelchairs [8]. Most of the current literature proposes leveraging the electronic systems in power wheelchairs for dynamic cushion designs. In our work, we proposed borrowing from advances in the field of soft robotics and wearable technologies [9] to shrink the footprint of the electronics. This will allow us to create a dynamic cushion system that is lightweight and can be implemented in manual wheelchairs to broaden the application of these designs.

Currently, soft, flexible sensors are being explored in wearable designs. A custom capacitance sensor matrix was developed for mapping foot sole pressure even during dynamic motions [10]. Additionally, pressure sensing strips were wrapped around the lower leg area to monitor venous leg ulcers [11]. Other flexible sensors used on the body include smart clothing devices, which have utilized conductive yarn, custom electrodes, and silicones. Data collected from smart clothing can influence emotional care, disease prevention, and lead to active medical response in emergency situations [12],[13]. A variety of wearable technologies surveyed use capacitive and resistive sensors. While capacitance sensors allow for greater customization, introducing variability in sensor fabrication, may lead to inaccurate measurements across a map [14]. In this work, we focused on developing a resistive sensor enabled design that can be customized to the user and provide dynamic response to developing pressure sores.

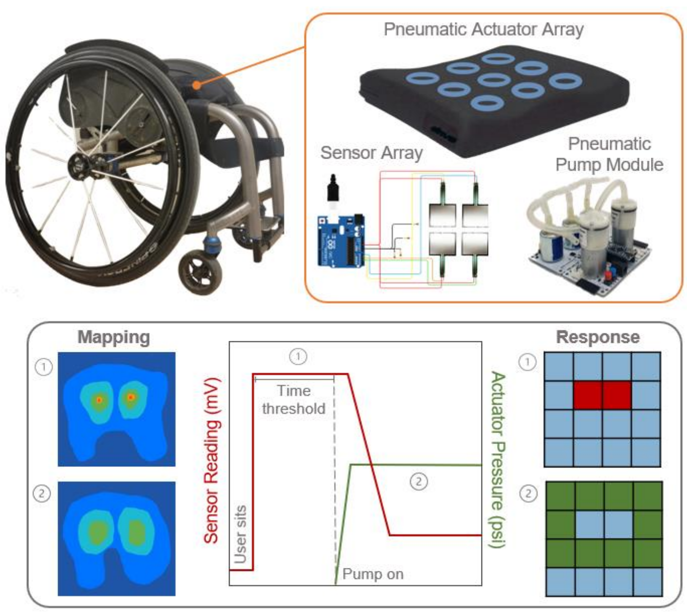

FIGURE 1: SCHEMATIC REPRESENTING DESIGN CONCEPT.

2. DESIGN OF A DYNAMIC SEAT CUSHION

To address the shortcomings of current technologies developed for seat cushions, we propose a new dynamic wheelchair cushion using a resistive sensor array to map magnitude and duration of applied pressure. Additionally, custom polymeric bladders will actuate in response to sensor readings to redistribute pressure across the cushion. Figure 1 shows a conceptual schematic of proposed design elements (top) and functional elements of the proposed use case (bottom).

2.1 User-Centered Design

Stakeholder input from clinicians, researchers, athletic trainers, and wheelchair users was used to inform design of the active and adaptive cushion. Thematic analysis was used to create stakeholder summaries in Table 1. Common feedback included (1) the necessity of a design that was specific and adjustable to the user's lifestyle, (2) providing the area affected with proper blood flow and circulation, and (3) creating a breathable design that reduces factors like high temperature and humidity. With this feedback, we sought to develop a wheelchair cushion to address these design criteria.

TABLE 1: SUMMARIZED FEEDBACK FROM STAKEHOLDER INTERVIEWS.

Stakeholder	***Priorities in Design***
Clinicians	• Affordability • Humid environment may cause infection • Gel foam is state-of-the-art material • Treatment and prevention are patient specific
Researchers	• Prevention is priority because treatment is tedious and lengthy • Humidity should be reduced • Temperature should remain low (T_{room}) • Center of gravity shouldn't change when in use
Athletic Trainers	• Treatment should be specific to the individual • Individuals' lifestyle will impact use • Providing the wound with proper blood circulation facilitates healing
Wheelchair Users	• Automatic redistribution of pressure and weight • Seat should be highly comfortable to support due to lack of gluteal muscles in some users • Customizable

2.2 Design of a Dynamic Seat Cushion

To develop a closed-loop active seat cushion design, we propose the following technical workflow shown in Figure 2. In our design we will have a wheelchair cushion embedded with resistive sensors as well as custom polymeric pneumatic bladders. By placing the sensors and bladders in a grid design, we can pinpoint areas of high pressure and adjust the cushion to redistribute the pressure across the cushion. To detect areas of high pressure, we read a voltage drop across a 10 kΩ resistor. A microcontroller (Arduino) reads and collects data. When the user sits on the cushion and an area of high pressure is detected for an extended time period, as determined in consultation with clinicians, the cushion will inflate the bladders of the surrounding cells to displace the pressure across the cushion. Inflation will be controlled by a pump (Programmable Air). After a period of inflation, the bladder will then deflate, and this cycle will repeat during use. To develop this design, we next tested sensors for durability and sensitivity.

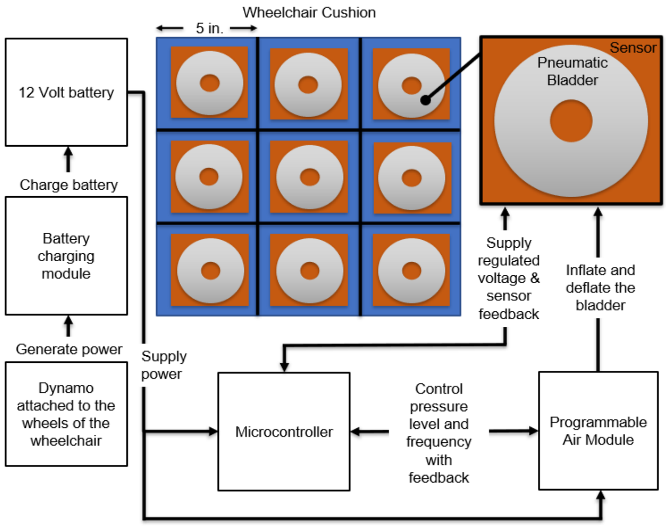

FIGURE 2: SCHEMATIC REPRESENTING TECHNICAL FLOW OF DESIGN.

2.3 Controls Design and Testing

For device design and testing we used a 12-volt battery powered microcontroller (Arduino Uno). From there, when pressure is applied to a sensor, the Arduino will supply feedback to the Programmable Air device, thereby inflating the pneumatic bladders. The pump inflates bladders until it reads a specified pressure in each bladder and then stops inflating. Once the programmed inflation period passes the bladder deflates returning the bladders and cushion to their original position. In the future, the battery will charge using a dynamo attached to the wheelchair user's wheels. This will ensure that the battery does not run out of power and the device will be able to work for long periods of time (Figure 2).

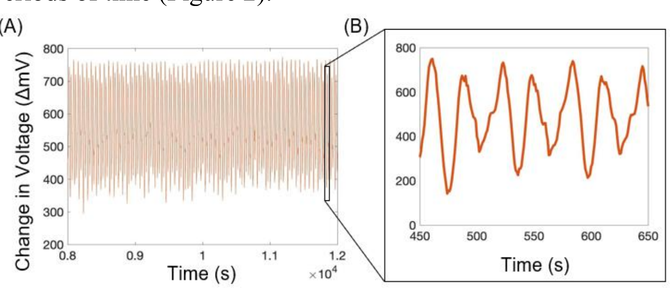

FIGURE 3: SENSOR DURABILITY TESTING. (A) SENSOR READINGS OVER 1 HOUR OF TESTING, (B) 3.5 CYCLES OF SENSOR TESTING.

In a seat cushion design, sensors will experience, at a minimum, 1,400 – 3,000 loading cycles per year [15]. To ensure that FSR UX 406 (Interlink Electronics) sensors will operate under cyclic loading conditions, we tested the sensors over 57,000 cycles at a rate of 7,200 cycles/hour using a custom testing apparatus. A rotating elliptical body applied variable pressure on the sensor, which was attached to a spring-loaded surface to dampen vibrations caused by the rotational motion. Maximum pressure measured by the sensor was recorded to test the durability and reliability of the sensor. There was no significant change in the maximum value after testing the sensor for 57,000 cycles, the results were consistent and there was no damage caused to the sensor and the pressure cycle outputs were consistent as shown in Figure 3.

By placing the sensors in a 2x2 array, we tested the ability to read variable pressure values. Figure 4 shows three configurations of pressure application to the sensor array. By conducting these tests, we can see that when a user shifts their weight and changes positions, we will still be able to accurately read the force they are applying to the sensor. Combining results from durability testing (Figure 3) and mapping (Figure 4) we have confidence that this sensor array will provide input data needed for the dynamic cushion design.

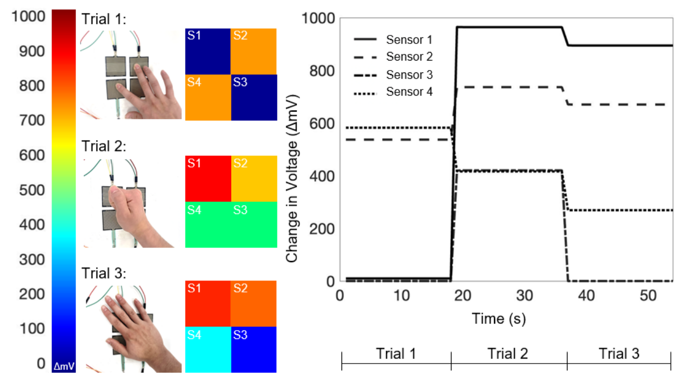

FIGURE 4: PRESSURE MAPPING TRIALS

2.4 Bladder Models

During the concept stages of the bladder fabrication process, we used SolidWorks 2022 to design 3D models. In SolidWorks, we experimented heuristically with basic geometries that best fit the design criteria. After gathering measurements from a personal wheelchair cushion, we designed three concepts that fit our cushion parameters: a rectangular prism, a triangular prism, and a torus (Figure 5), using the fillet tool to round edges to reduce stress concentrations in final pneumatic bladders. A primary goal in developing bladder geometries is user comfort and strength to support body weight. Based on our interviews with clinicians, we selected the torus concept. Not only is the torus shape being used in the medical field, but according to interviews conducted by our team, some clinicians who work with elderly patients suffering from pressure sores use torus-shaped medical devices for support and balance [16]. There are also torus-shaped medical devices available online (MedicalExpo) for purchase that act as comfort support for office chairs and other sitting surfaces.

2.3 Fabricating Bladders

Custom bladders were fabricated following a previously published protocol [17]. In short, two thermoplastic polyurethane sheets were heat-sealed with a tubing adapter inside, connected once the sealing process was complete. During development of the pneumatic bladder fabrication process, constructs underwent several durability tests that demonstrated the permanence of the bladder up to 38.68kPa [16]. This fabrication process will produce bladders with strength to support average users with average seat cushion sizes. Once the fabrication process is complete, a modified barbed fitting is attached with hex driver. The threads on the barbed fitting cut a hole in the material. The barb was then unscrewed, then an o-ring was placed on the barb, and finally the barb was secured. Moving forward, pneumatic tubing can be attached to the adapter to inflate and deflate the designs.

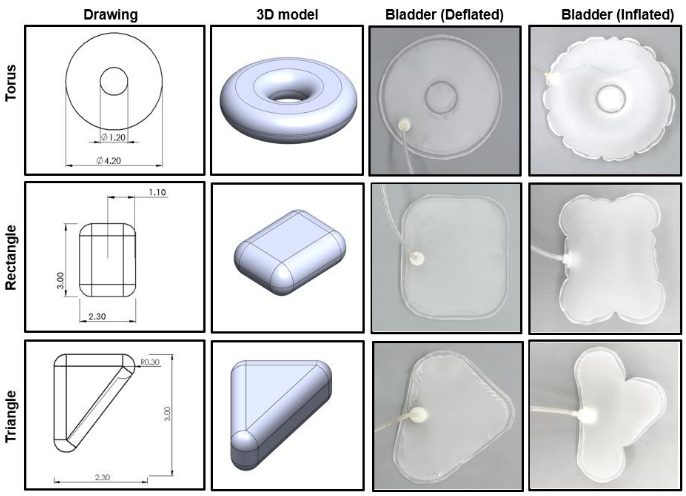

FIGURE 5: DESIGN CONCEPTS FOR PNEUMATIC BLADDERS.

2.4 Pneumatics

For inflation and deflation of the customized bladders, we used a Programmable-Air controller (tinkrmind.me), which allowed us to have a programmable pneumatic system. The system consists of two motors that pump air in and out of the bladders and three solenoids to control the valves and ultimately the air flow. Multiple control systems can be connected to increase the number of valves and pumps. As pressure increases in some region, the Programmable-Air pumps air in the bladders surrounding that region and inflates them until 16psi when no external load is put on the bladders. A 2SMPP-03 (Omron) pressure sensor is used in the Programmable-Air unit which reads this pressure inside the bladders and provides us the required feedback to compare with the set threshold.

2.5 Systems Integration

Once sensor testing, bladder fabrication, and pneumatics were complete, we compiled the system for testing. Our system contains a rigid base with four sensors placed in a 2x2 array with pneumatic bladders on top of each. Controls are situated under a commercially available foam cushion. We tested a variety of scenarios, an example shown in Figure 6. We began testing with all bladders inflated. In this position all sensors were experiencing equal pressure. To demonstrate alleviating pressure in one area, we inflated three bladders surrounding that area. We can see that this relieves all pressure from one sensor and distributes it onto three sensors. The weight remained stable on top of the inflated bladders, with one sensor increasing reading due to the shifting weight. This testing covered a scenario when the pressure builds at one corner of the cushion.

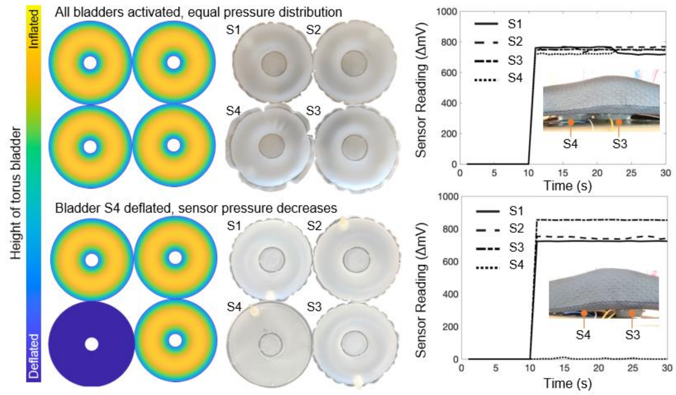

FIGURE 6: TESTING SENSOR-BLADDER INTERACTIONS.

2.6 Conceptual Designs

From testing our system on a smaller scale, we can see how it can translate to a full 9x9 array or larger. When sensors detect a region or cell with high pressure, the surrounding cells will inflate to offset the pressure distributing it evenly. Increasing number of bladders will create a honeycomb effect, providing pockets of air for breathability and stability. When the cushion actuates and pressure is redistributed, users will decrease the dangerous levels of pressure on the affected area minimizing risk of pressure sore development. When this area is isolated, blood will flow normally to the area and the body will be able to heal properly. Finally, our design can adapt to all lifestyles, allowing all wheelchair users to live an active life and reduce burden of hospital visits and bed rest.

3. CONCLUSION

Our proposed dynamic seat cushion uses resistive sensors, a programmable pneumatic pump, and thermoplastic polyurethane bladders to create a custom technology with the goal of preventing pressure sores in wheelchair users. Leveraging custom fabrication methods for pneumatic bladders, we can customize seat cushion designs and bladder geometry and placement based on user needs. Inspired by designs from wearable and soft robots, we can reduce the footprint of electronics to reduce burden of implementing this cushion design. There are great opportunities to improve prevention and treatment of pressure sores in the medical field. As we developed each characteristic of this cushion design, we were able to understand further the needs of wheelchair users and the technical logistics required. We believe further developing these critical characteristics will give us novel insight into pressure sores while providing options for prevention and treatment.

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