SMART CUSHION

A Final Year Project Report

Presented to

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

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In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

by

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ABSTRACT

This project aims at developing a locally manufactured affordable air inflated smart cushion to avoid pressure ulcers being developed in the patient's skin, seated on a wheelchair for extended periods of time. Pressure ulcer is a skin and tissue condition which develops due to constant pressure on a part of the body for prolonged periods of time. This condition is usually seen in bed-ridden or wheelchair-ridden patients who experience this constant pressure on the lower part of their bodies due to their own weight.

Our smart cushion will have two main modes namely preset mode and feedback mode. Furthermore, the cushion will have 11 compartments with pressure sensors on top of each. Feedback mode will change pressure of the compartments by taking feedback from the installed pressure sensors. Preset mode works on predetermined time to change the pressure of the compartments to avoid pressure sores to develop.

Currently, there are no such products available in Pakistan. A few products are commercially available in the international market, but they are very expensive and have high shipping costs.

ACKNOWLEDGMENTS

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ABBREVIATIONS

SCI	Spinal Cord Injury
ADC	Air Distribution Center
PU	Polyurethane
APAM	Alternating Pressure Air Inflated Mattress
VFM	Viscoelastic Foam Mattress
FSR	Force Sensitive Resist

CHAPTER 1: INTRODUCTION

Motivation

It has been estimated that approximately 17,730 people suffer from life altering Spinal Cord Injury (SCI) in USA alone (1). These patients are forced to remain seated in a wheelchair for unhealthy periods of time, leading to pressure ulcers. This is a highly unaddressed issue in Pakistan with little or no awareness. Currently, there are no preventive measures taken by the Pakistan's healthcare system to avoid pressure ulcers to be developed in bed-ridden or wheelchair-ridden patients. Furthermore, there is no such product available in the local market, and the available products in the international market are very expensive.

According to Pakistan Bureau of Statistics (PBS) there are almost 9000-10000 annual accidents in Pakistan (2). A considerable number of them results in SCI in the people involved. Due to the SCI, the patients have restricted or no movement. This results in damage to the skin and underlying tissue due to the constant weight of the body.

Pressure ulcers is a skin and underlying tissue damage due to a constant pressure on a part of the body for unhealthy periods of time. Immobile patients suffer from this condition due to the weight of the body being constantly applied. Smart Cushion aims at developing a compartmentalized cushion which can change pressures alternatively to enable skin perfusions and avoid pressure sores to be developed.

The treatment of pressure ulcers can cost up to $70,000 (3). In severe cases, amputation may be required. Considering Pakistan's financial situation and low buying power of the public, the high treatment costs for these types of conditions are unbearable. Hence, to provide a cheap solution to avoid this condition is a necessity.

This smart cushion is designed with the intent of being used with any standard wheelchair, hence removing the complications of custom designed wheelchairs. The design of the cushion can be extrapolated for beds to help the bed-ridden patients as well.

Problem Statement

The aim of this project is to develop an affordable air inflated smart cushion that can be locally manufactured and works on both preset values of time as well as take feedback from the pressure sensors to make intelligent decisions. The problem statement can be divided into three main categories which are listed as follows:

1. **Cost Effective Solution:**

   Since the budget of the healthcare system of Pakistan is limited and the buying power of the locals is low, the need for cheaply manufactured product becomes a necessity. Hence, providing a cost-effective product is a problem that we tackled in this project.

2. **Design:**

   To enable skin perfusions and avoid pressure sores to be developed in the patient, a compartmentalized cushion that can alternate pressure at different contact points was essential. Furthermore, a control system that can take feedback from the cushion-patient contact pressures and send signal to the actuation mechanism accordingly was necessary.

3. **Manufacture Locally:**

   To make use of locally available materials and vendors was an objective kept in perspective. This made sure that the cushion can be manufactured and made available cheaper than the products in the international market.

Objectives

The objectives of this projects are set according to the deliverables. The objectives can be listed as follows:

1. **Perform literature review and market survey:**

   Study of research papers to find possible solutions to the problems regarding design, actuation mechanism, feedback system, material selection and analysis. Furthermore, perform a market survey to define our target market.

2. **Design Cushion, Analyze and select Material:**

   Using modelling and analysis software such as SolidWorks to design the cushion compartments and perform stress and impact analysis. Furthermore, perform failure analysis on the material selected.

3. **Design of an actuation mechanism and integration of feedback system:**

   Using pump, solenoid valves and a pipe network to design an actuation mechanism for the air inflated cushion. Integrating the network to a control system by programming valves and pump with the feedback from the pressure sensors. Furthermore, program Arduino to control the valves and pump according to predefined safe limits.

4. **Perform the Economic Feasibility Study and Cost Analysis:**

   Using locally available vendors and materials to design our cushion to make it cost effective. Moreover, manufacture the cushion locally to make it cheap.

5. **Make a prototype for proof of concept:**

   Test our control system using network of pumps, valves, ADC, and a pipe network to visually represent the effect on two compartments. Test for both feedback and preset codes.

CHAPTER 2: LITERATURE REVIEW

Pressure Ulcers

Pressure ulcers are a type of injury in which the skin tissue breaks because of unavailability of oxygen supply and nutrition due to constant pressure application on the skin resulting in tissue ischemia and later, tissue necrosis. Majority of people who are at risk of pressure ulcer development are those suffering from mental or physical illnesses that prevent them from moving their bodies, such as spinal cord injury (SCI) patients. Additionally, old age (60 – 80 years) also increases the risk of pressure ulcer development.

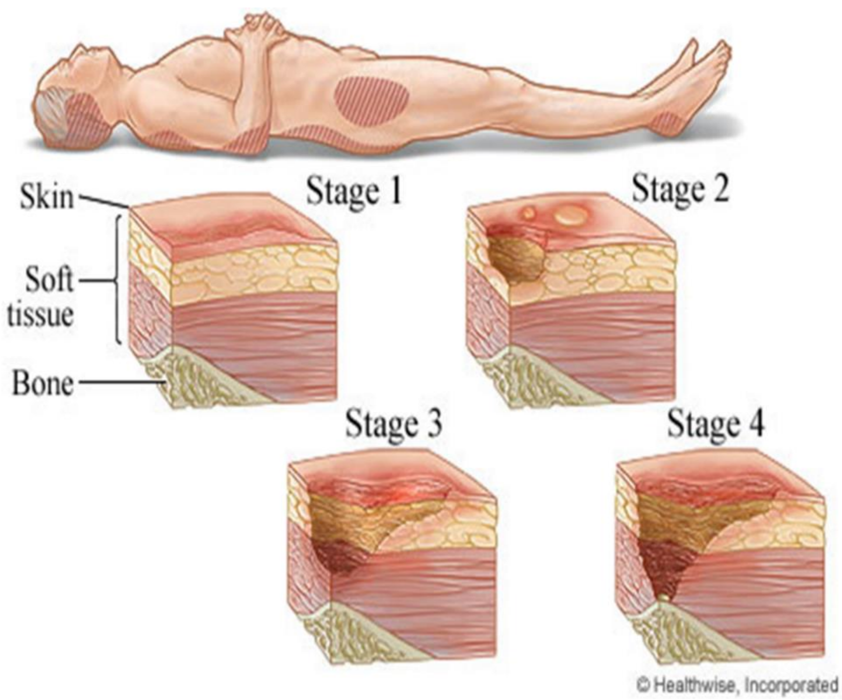


Figure 1: **Stages of pressure ulcer severity** (4).

In order to gauge the severity of pressure ulcers, healthcare professionals use stages or grades. They are categorized into four stages.

Stage 1 is the most superficial stage of pressure ulcer development. The affected skin turns red or dark. This discoloration can also be accompanied by a burning or itching sensation. The damage done in this stage is easily reversible and the patient can heal in about 3 days.

In stage 2, the skin tissue has suffered some damage and it may have open sores or blisters. The patient may feel significant pain and discomfort in this stage. With proper medical attention and cleaning, this sage can heal in about three days to three weeks.

In stage 3, the pressure ulcer has broken down the top two layers of skin and has reached the fatty layer below. The ulcer, in this stage, resembles a crater and it may also smell foul. This stage requires immediate medical attention, and it can take up to four months to heal.

Stage 4 is the most severe stage of pressure ulcer development. In this stage, the pressure ulcer has completely damaged the skin tissue in the affected area and has extended below the fatty layer, into muscle tissue and bones. This stage accompanies significant pain, drainage, and a high risk of infection. The patient needs to be hospitalized immediately and surgery may be required. Complete healing can take up to two years in worst cases.

Now, as stated earlier, pressure ulcers develop due to application of certain values of pressure on the skin for certain periods of time. This correlation of pressure application and the period for which it is required to be applied to develop a pressure ulcer is extremely important.

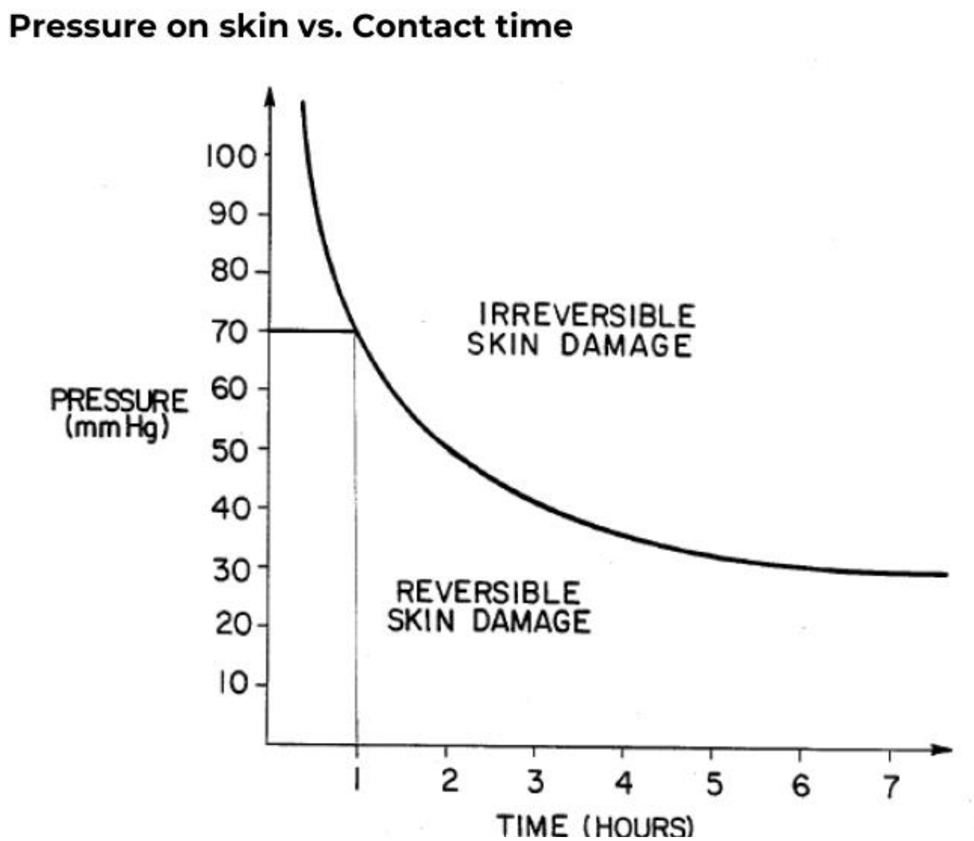


Figure 2: The relationship between applied skin pressure and time period (5).

The figure above shows the relationship between pressure applied on skin to the period it is applied. It can be observed that pressure of 30 mmHg is safe for human skin. Below this pressure, human skin can theoretically never develop a pressure ulcer, irrespective of the time that pressure is applied. This relationship between pressure and time of application is a major consideration in the operation of our device to prevent pressure ulcer formation.

Skin Perfusion

This smart cushion helps in prevention of pressure ulcer formation by promoting skin perfusion through alternating pressure. Skin perfusion is the passage of blood through the circulatory system of the skin tissue. According to a research, the alternating pressure manipulates the stress and strain developed in skin tissue which elicits local vasodilatory response to maintain tissue viability. This is extremely beneficial for spinal cord injury (SCI) patients who remain stationary due to not having the ability to move their bodies.

In the same research, a comparison between effect of constant pressure and alternating pressure application on skin perfusion in healthy people and SCI patients.

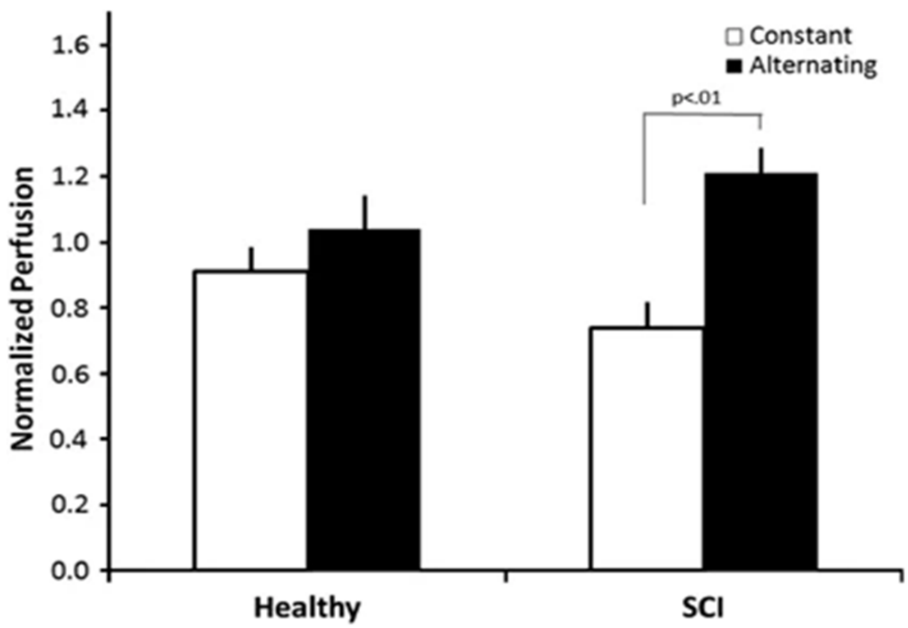


Figure 3: Effect of constant and alternating pressure on skin perfusion. (6)

In figure 3, it can be observed that in healthy people, alternating pressure induces greater skin perfusion as compared to constant pressure. For SCI patients, this gap is even more significant, with alternating pressure application inducing significantly greater skin perfusion as compared to constant pressure application.

Thus, the benefit of alternating-pressure air-inflated cushion for healthy people as well as SCI patients is undeniable.

Necessity of the Project

In order to address the highly pressing issue of pressure ulcer development in Spinal Cord Injury (SCI) patients, efforts have been made globally in development of preventive measures. Out of these preventive measures, alternating-pressure air-inflated cushions and mattresses (APAM) are considerably more effective at preventing the development of pressure ulcers when compared to other standard measures of prevention according to studies and research carried out (7). The studies show a comparison between APAM cushions and Viscoelastic Foam Mattresses (VFM). It was discovered that the risk of pressure ulcer development from using APAM was 6.46%. On the other hand, the risk of pressure ulcer development from using VFM was 38.91%. Users of VFM were 7.57 times more likely to develop pressure ulcer as compared to the users of APAM.

Additionally, cushions and mattresses that sense pressure and make smart decisions by inflating or deflating only the required compartments, thus making them more efficient, are extremely rare. This fact is one of the novelties of our project.

After carrying out a market survey, it was discovered that such cushions or mattresses were not available in Pakistan, and they had to be imported from abroad. This increased their price well above the reach of general public. Thus, to resolve this highly unaddressed issue in Pakistan, we aim to develop an air inflated cushion that can be manufactured cheaply and can also sense pressure of the seated person and make smart decisions in inflating and deflating the required compartments to prevent the development of pressure ulcers.

Market Survey

Market survey reveals different types of products available that aim to hinder the development of pressure ulcers. Two of these products are air inflated plastic cushions and memory foam cushions.

Figure 4: Air inflated plastic cushion (left), Memory foam cushion (right)

While these products do offer some protection against pressure ulcer development by redistribution sitting pressure and are relatively cheap, their performance is not very convincing. This is because they are constant pressure redistributing apparatus and as stated earlier, alternating pressure encourages skin perfusion at a larger scale and hence is a lot better at pressure ulcer prevention.

The other product available is air pressure alternating cushion which is the main type of product used for pressure ulcer prevention.

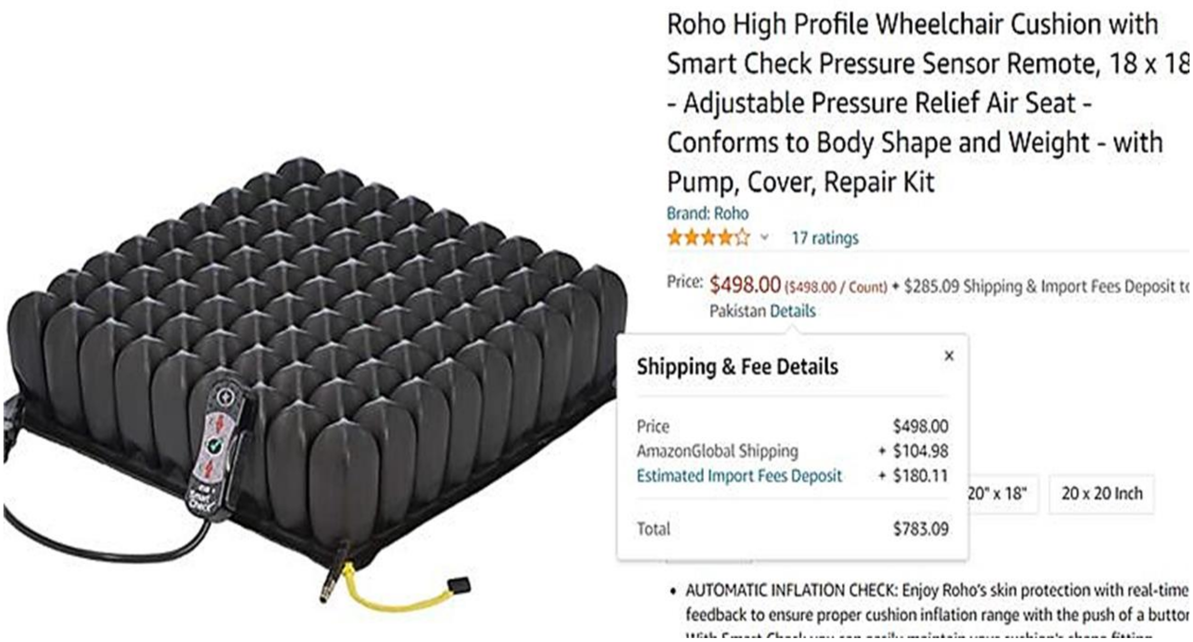


Figure 5: Pressure alternating air cushion (8)

This product alters pressure of its various compartments at regular time intervals. As shown through research, this enhances skin perfusion and greatly lowers the risk of pressure ulcer development. Another feature offered by this device is the ability to sense pressure and allowing the user to redistribute air in its various compartment as they see fit. Although the device is quite useful, it lacks the utility of automatic identification of high-pressure compartments to inflate and deflate them accordingly. It also lacks various other functions and utilities like storage of pressure data for doctors and pressure data display on an application and website. Additionally, this product boasts quite a hefty price tag and due to its local unavailability, it must be imported. The added shipping costs push its price far above Rs. 100,000, moving it beyond the reach of general public of Pakistan.

Actuation Mechanism

The choice of actuation mechanism to move the compartments of the cushion for pressure redistribution was among two modes, pneumatic actuation and mechanical actuation. Mechanical actuation involved motors and series of gears and rods to raise or lower sections of the cushion or bed. In pneumatic actuation, an air pump and air valves are used to inflate and deflate different compartments of the cushion. Mechanical actuation, due to having many moving mechanical parts, was prone to wear and tear and high energy consumption. Pneumatic actuation, on the other hand, did not have these drawbacks. Thus, pneumatic actuation was incorporated in our device.

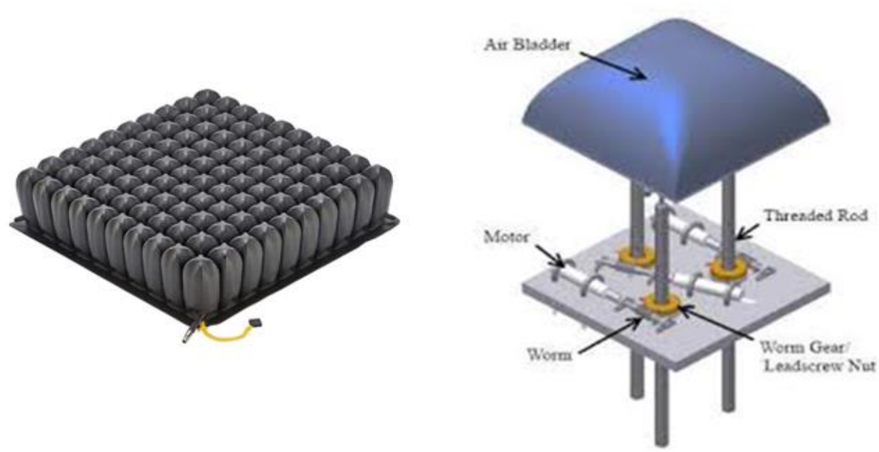


Figure 6: Pneumatic actuation (left), Mechanical actuation (right),

Material and Components

The choice of material for cushion compartments was of utmost importance. For this purpose, materials used in the manufacture of various cushions were examined. Two materials shortlisted were Polyurethane leather and Neoprene fabric.

Polyurethane (PU) leather is used to manufacture cushions, seat covers, bags, shoes etc. This is a synthetic fabric made up of thermoplastic polymer. It is very tough, durable and, depending on the quality, does not wear down easily. Additionally, it is water resistant and mostly non breathable (9). All these qualities make it suitable for our device.

Neoprene fabric is a synthetic elastomer. It is used tin the manufacture of diving suits, sportswear, athletic equipment, automotive gaskets etc. It is impermeable and does not allow anything to pass through it. It is highly elastic and can be shaped easily. It is water resistant, heat resistant and can easily withstand wear and tear (10). Thus, these characteristics make it highly suitable for our device.

Next factor to consider was the price of both materials. After a survey of online stores, it was discovered that the price of neoprene fabric ranged from Rs. 185 to Rs. 500 per meter, depending on the quality (11). While the price of PU leather hovered around Rs. 300 per yard (12). Neoprene fabric tends to get expensive, if higher quality is chosen, thus, considering the price and properties, we went ahead with PU leather as the material for the cushion.

Now, for the components of the device, the first constituent was the microcontroller to control and monitor all the functions of the device. Due to the cushion having 11 compartments, it needed 11 valves, excluding the exhaust valve, and 11 pressure sensors, one for each compartment. Including additional peripheral components, this amounted to many pins to cater for. Thus, Arduino MEGA 2560 was chosen as the microcontroller. It boasts 54 digital input/output pins and 16 analogue pins which are more than enough for all the components of our device. Furthermore, it a flash memory of 256 KBs, making it capable of storing programs of large sizes.

Figure 7: Arduino MEGA 2560.

Secondly, to control air flow, 12-volt DC solenoid valves were chosen. They have an opening size of ¼ inches. These solenoid valves are normally closed and direct acting, capable of being easily controlled by Arduino MEGA. They are extremely quick in their operation, making them highly suitable for control of air flow in the cushion.

Figure 8: 12-volt DC Solenoid Valve.

Thirdly, to sense the pressure of a seated person, Force Sensitive Resistors (FSR) are used. These resistors are placed on top of each compartment to gauge the force applied when a person sits on the cushion, which is subsequently converted to pressure. They have a surface diameter of 0.5 inches and each sensor can sense up to 100 Newtons of force.

Figure 9: 0.5-inch Force Sensitive Resistor.

Fourthly, to provide the required air supply, a 12-volt DC mini air compressor. It has a volume flow rate of 3 Liters per minute and maximum pressure limit of 2 bars. Considering the volume of each compartment, the airflow rate of 3 liters per minute is more than enough to inflate them quickly and a pressure limit of 2 bars enables the pump to continue pumping air without the risk of backflow even when a person is seated on the cushion.

Figure 10: 12-volt DC Solenoid Valve.

Lastly, other components include a 16 by 2 LCD screen to display pressure sensor data. 5-volt relays that can be controlled by Arduino to power solenoid valves and the Air compressor. An SD card module to store pressure data and Wi-Fi/Bluetooth modules to display pressure data on an app and website, respectively.

CHAPTER 3: METHODOLOGY

After completing the literature review this section explains our approach to designing and developing the cushion followed by a detailed stress analysis on the behavior of the cushion and skin conditions under loading.

Cushion Design:

The objective of this part was to come up with a design for our smart cushion that allows us to have different compartments, each of which can be inflated or deflated individually. The location, geometry and size of each compartment was also a considerable factor in designing the cushion as it had to be made sure that with each inflation/deflation of a compartment we can reduce the pressure on the person's skin and increase comfort. Finally, cost analysis also had to be kept in mind as the increase of one compartment would lead to a cost increment of about Rs. 2500 which included Rs. 1500 for an electromagnetic valve (13) and Rs. 1000 for a force resistor (Pressure sensor) (14).

The initial approach was to design a 400mm-by-400mm square cushion with 16 compartments (4x4). We were then required to simplify the design and reduce the compartments in order to reduce the overall cost and decrease the complexity in manufacturing the cushion.

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Figure 11: Initial 4x4 compartment concept

To do that we referred to pressure map data of a person sitting on a seat/cushion (15), one such map has been shown in the given figure. The idea was to ensure that we have a higher number of compartments available at regions with higher pressure so that at those points we have greater capability of controlling the pressure. The compartments in lower pressure regions that were closer to each other and showed similar pressure characteristics on the pressure map were decided to be merged thus reducing the number of compartments.

The final cushion design consists of 11 compartments, with 8 compartments towards the central part, 1 long compartment towards the person's back and 2 compartments to vary the pressure on each of the person's thighs. This configuration was chosen based on the pressure region seen on the map. The mid region is where the highest pressure is formed (yellow and red regions) thus with 8 compartments there we can reduce the pressure better. The pressure towards the person back is quite low and is almost the same throughout thus a single compartment was considered suitable. Similarly, the pressure on each of the thighs is low as well as well distributed hence giving them a single compartment each too. The dimensions of each of the compartments was also decided based on the pressure distribution from the map data.

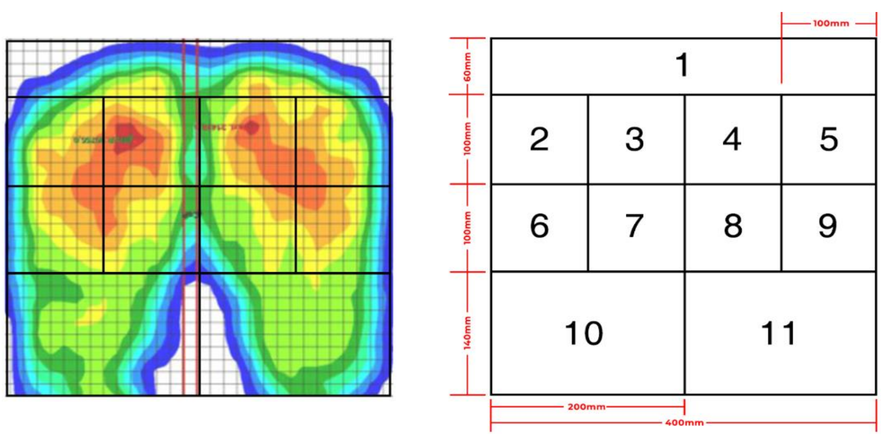


Figure 12: Final compartment design (right) based on the pressure map (left)

CAD Model Design

A basic CAD model of the cushion designed in solidworks showing all the individual compartments:

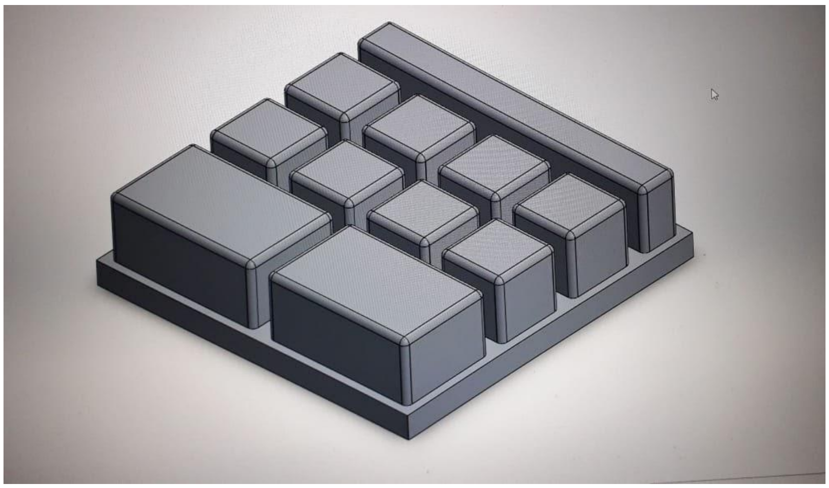


Figure 13: Initial CAD Model

Pressure sensor placement:

It is important to decide on how the pressure for each compartment would be measured and where the sensor would have to be placed. The main options that we could use to measure the pressure was either using pressure sensors/ force resistors or by using a pressure pad. The individual pressure sensors would have to be mounted on each of the compartment separately while the pressure pad could only be placed below the whole smart cushion device due to the way the top of the cushion works. This creates the inability of the pressure pad to measure the pressure on each part of the skin accurately. This factor coupled with the cost analysis of each method allowed us to decide that using individual force resistors as pressure sensors was the better way to measure the pressure on the skin at each compartment.

Cushion Working Schematic:

With the cushion design and sensor placement finalized, it is important to view the complete basic working of the cushion. In order to achieve that a schematic diagram has been created as shown in the figure. This diagram represents all the parts involved in the smart cushion and the way they work along with each other.

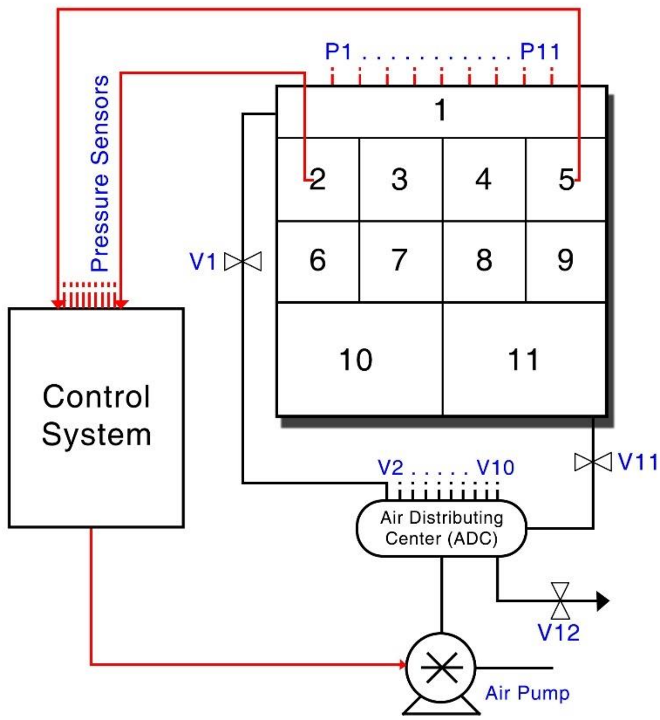


Figure 14: Cushion working schematic

The cushion is the most vital part of the whole system. It consists of 11 compartments each having the capability to inflate and deflate depending on the pressure exerted on them. The pressure sensors are attached on top of each compartment and are responsible for sending the respective compartmental pressure data to the control system (The respective signal path is indicated as red arrows coming out from the cushion) once a person is seated. This data is analyzed at a certain time setting by the control system and compared against the safe pressure values/ranges embedded into the system. Pressure values that exceed the given safe ranges will trigger a signal from the control system to the air pump (signal path shown in red from control system to air pump) as well as the required valves depending on the region and whether inflation or deflation is required.

Inflation/Deflation mechanism

This part of the system deals with the motion of air in and out of each compartment depending on the signal received from the control system.

The ADC lies at the center of this mechanism. It is a small chamber that ensures the air flow from the pump into each compartment as well as exhaust from each compartment into the atmosphere without producing any backflow into the air pump. The small size of the ADC is to ensure that any pressure loss due to the ADC is minimal/negligible.

During the inflation process the control system sends signals to:

- Air pump to turn on allowing air into the ADC
- The respective valve/s (Vx) of the compartment/s that need to be inflated to open.
- Once inflated and safe pressure values obtained (checked by compartmental pressure sensor) all valves, and the pump will turn off.

While during the deflation process signals are sent to:

- The respective valve/s (Vx) of the compartment/s that need to be deflated to open.
- Valve V12 to open thus allowing air to escape into the atmosphere.
- Once deflated and safe pressure values obtained (checked by compartmental pressure sensor) all valves will turn off.

These chains of command can however be slightly changed or halted at times by the air pressure sensor that is connected to the ADC. This is to ensure that there is not any unnecessary backflow between a compartment and the ADC or the ADC and the pump.

Control System

Design Parameters:

The parameters that we had to keep in mind while designing the Control systems were the stresses on human skin and the time for which the patient/user experienced them. Now the concept of skin perfusion plays a vital role in preventing pressure ulcers in patients, to provide the required skin perfusion, according to the needs of the user, we introduced 3 modes.

1. Preset mode (Patient):

During the literature review, we found out that most of the commercial products inflate and deflate their compartments every 5 minutes (16). Our preset mode, the one designed for patients does the same, it inflates and deflates the compartments in a specified manner, as mentioned below.

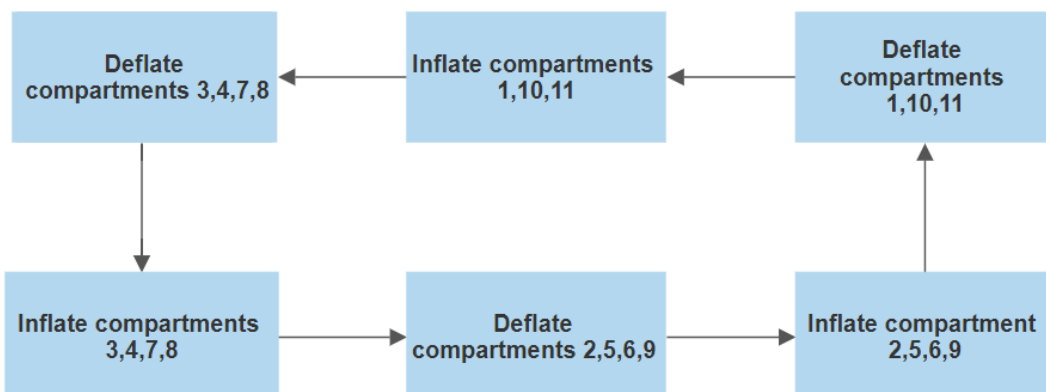


Figure 15: Inflation/Deflation specification after every 5 minutes

2. Preset mode (Regular):

To further broaden the scope of our project and increase the target audience, we have introduced a Regular Use Preset Mode, it is designed for the office use or for people who must sit for considerably long periods of time. During the Pandemic, Work from home became a necessity and the restriction on movement led to people being confined to their homes most of the time. This considerably increased the sitting time in a people's lives, and in some cases to unhealthy levels. This preset mode is specifically designed to address this situation, its working is explained below.

It inflates and deflates the compartments in a specified manner (like patient mode) every 10 minutes as the requirement for skin perfusion is not as high in normal people as it is in patients, the reason being their more active lifestyle and frequent use of muscles.

3. Feedback Mode:

Now this is something most commercial products fail to provide, a system the decides the compartments to be inflated and deflated according to the Stress being experienced by the human skin, and if a product offers something similar, you can expect the price to skyrocket and go as high as 2000 USD, which is way beyond the buying power of the people of our country.

Our feedback mode takes the reading from the Force Resistive Sensors (FSR) and according to predefined categories, identifies them as either low, medium, or high stress compartments. The low stress compartments are alternated once every cycle of our feedback loop while the medium and high stress compartments are alternated twice and thrice, respectively, in every cycle of our feedback loop.

The Categorization of compartments is based on the following limits:

- Low Stress Compartments: Below 80mmHg (100 to 500 units in the proof of concept)
- Medium Stress Compartments: Between 80mmHg to 100mmHg (500 to 800 units in the proof of concept)
- High Stress Compartments: Above 100mmHg (Above 800 units in the proof of concept)

Proof of Concept

In order to test the codes and demonstrate the operation of the cushion, a small-scale proof of concept has been built. It comprises of two balloons acting as two inflatable compartments. Two FSRs placed near the compartments act as pressure sensors. Three solenoid valves are used to control air flow. A plastic bottle is used as air distribution center. Instead of Arduino MEGA, we use Arduino UNO as a microcontroller due to lesser number of components and connections.

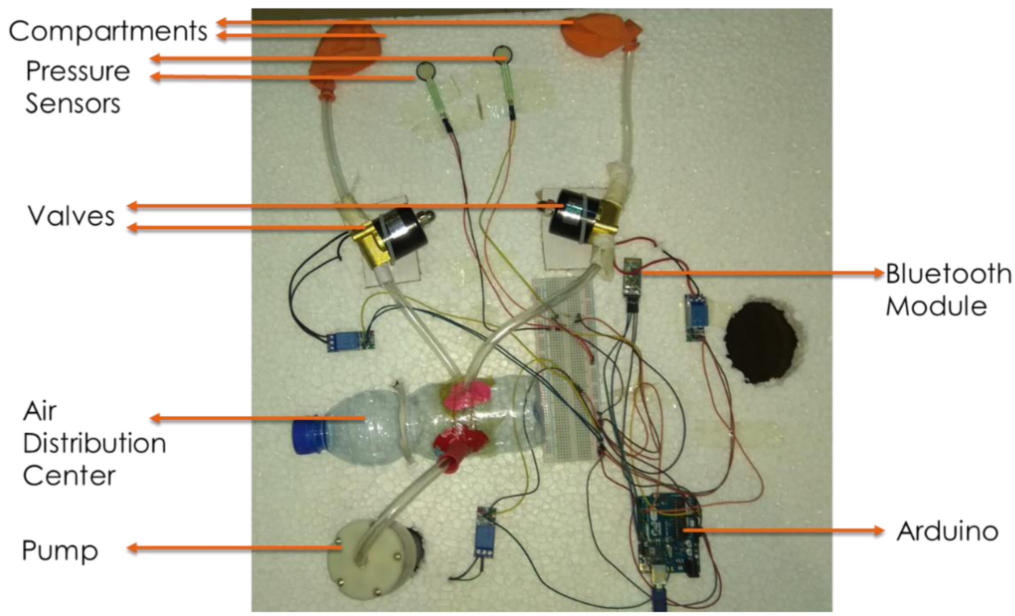


Figure 16: Proof of Concept

The proof of concept also works on two modes of operation i.e., preset mode and feedback mode. The links containing the video of demonstration of the two modes of the proof of concept have been provided in Appendix II.

A four-compartment proof of concept was also created to test the code on a larger number of compartments. This device has a frame built of wood and contains four balloons acting as inflatable compartments. The number of sensors has been increased to four and the number of solenoid valves have been increased to five, four valves for four compartments and one valve acting as exhaust. This proof of concept has a couple of four-way connectors acting as ADC which is closer to the ADC of the actual device.

Figure 17: Four-compartment proof of concept

User Interface Platforms

It was our aim to make this device as user friendly as possible. To this end, we included the service of a website. This website reads, records and plots the pressure data from the FSRs for a seated person. This data can help the doctors analyze the sitting conditions of the patients and aid them in devising a suitable prevention plan.

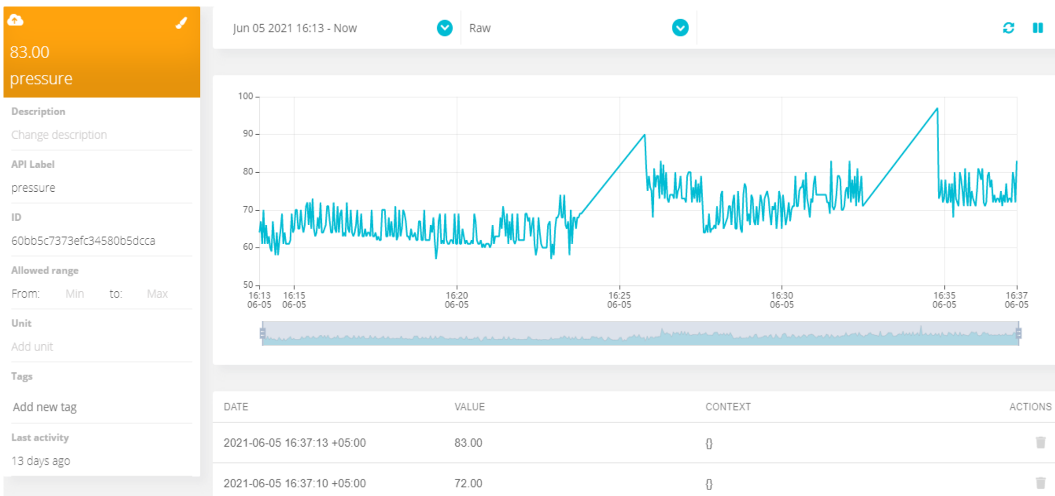


Figure 18: Website

We have also provided the services of a third-party android application, Ardutooth. This application displays live pressure data on a smartphone easily, thus increasing the user friendliness of the device.

Figure 19: Android Application

Stress Analysis:

The main objectives behind performing stress analysis were:

- Study the behavior of the cushion under loading and unloading.
- Study the pressures felt on the skin and how it varies with change in compartmental pressures.

Before proceeding with the stress analysis, we first require finding the accurate weight distribution to be applied on the cushion in order to obtain more detailed results.

Accurate Weight Distribution:

An actual seated person does not produce an equal weight distribution over the seated surface. By reproducing a weight distribution that is as close to the real scenario, we can increase the accuracy of our analysis. In order to accomplish this, a general pressure/weight distribution data (17) of a **70-75kg** seated person is evaluated. This evaluation is performed separately for the top and thigh parts due to different total masses to be distributed *(torso: **40 kg** and thighs:**10kg**).*

The pressure distribution (15) of the top part is shown below:

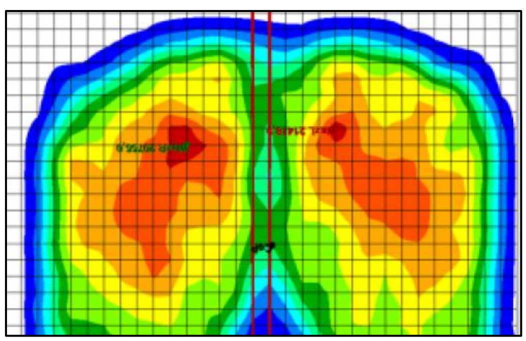


Figure 20: Top region pressure map

Using this data, we distribute the weight into 4 distinct regions with different pressures.

Red	Orange	Yellow/Green	Blue
19kPa	15kPa	11kPa	6kPa

Table 1: Pressure distributions based on the pressure map (top region)

This allowed us to create the split for the top part with areas computed using SolidWorks:

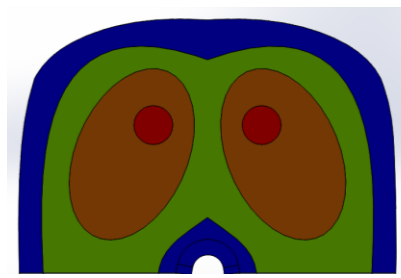


Figure 21: Top part split into different pressure regions

A_{Red}	A_{Orange}	$A_{Yellow/Green}$	A_{Blue}
0.00221824 m^2	0.02723399 m^2	0.03075867 m^2	0.01863267 m^2

Table 2: Section Areas

With the areas and pressures of each region known, the force ratios can be found using:

Force = Pressure x Area

F_{Red}	F_{Orange}	F_{Yellow}	F_{Blue}	Total
0.04214656	0.40850985	0.33834537	0.11179602	0.9007978

Table 3: Force ratios

These ratios can now be multiplied with the total mass of 40kg (gravity constant, cancels out) to get the respective mass distribution in each section.

M_{Red}	M_{orange}	M_{Yellow}	M_{Blue}
1.871521 kg	18.139913 kg	15.024254 kg	4.964311 kg

Table 4: Mass Distribution for the top region

Proceeding to the lower/thigh region:

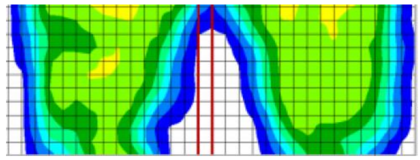


Figure 22: Bottom region pressure map

Unlike the top part this part has weight distributed into just two distinct regions:

Green	Blue
11 kPa	6 kPa

Table 5: Pressure distribution based on pressure map (lower region)

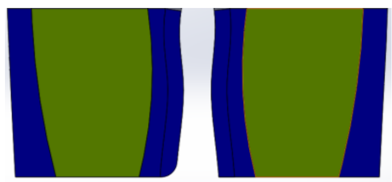


Figure 23: Lower part split into different pressure regions

A_{Green}	A_{Blue}
0.03335704 m^2	0.01387416 m^2

Table 6: Section Areas

F_{Green}	F_{Blue}	**Total**
0.36692744	0.08324496	**0.4501724**

Table 7: Force ratios

Since **total mass = 10kg** thus by using calculations similar to the top part we get:

M_{Green}	M_{Blue}
8.150820 kg	1.849180 kg

Table 8: Mass Distribution

Analysis:

The stress analysis could be performed in Solid works using two different approaches:

- *Solid model analysis:* Assuming the compartment to be completely solid with material properties that are the combined equivalent properties of air and PU leather.
- *Shell model analysis:* Using a shell model for the compartments. Each shell has the material properties of PU Leather and an internal pressure applied to each side which is equal to the pressure exerted by air in that compartment.

Solid model analysis:

No source was found for the combined equivalent properties of air and PU leather; thus, this analysis was then performed by using the material properties of SEMI-RIGID PU LEATHER FOAM (18) since it was the next closest option.

	Elastic modulus	Density	Poisson's ratio
Semi-rigid PU leather foam	0.92MPa	60kg/m^3	0.48
Skin (19)	60MPa	1020kg/m^3	0.4

Table 9: Material Properties

After applying accurate mass distribution to the model, following results were obtained.

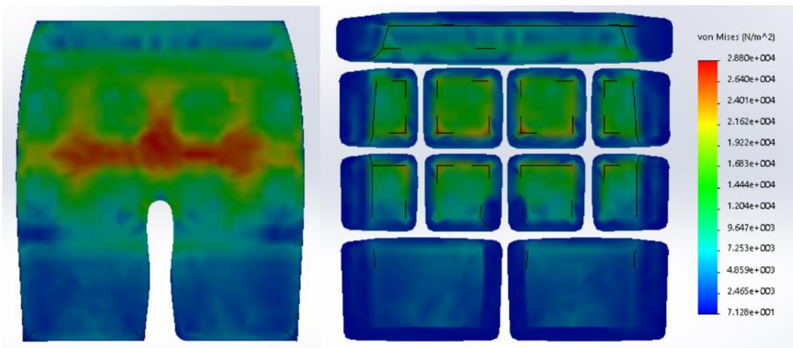


Figure 24: Stresses on the skin and cushion using the Solid model

Shell model analysis

The two types of loadings that were applied on this model were:

- External distributed mass
- Internal pressure on each side of the wall

The internal pressures were calculated using the mass distribution on each compartment to find the average pressures applied on each compartment. The pressure inside each compartment is set to be the same as the pressure applied on it in order to nullify the forces.

	Elastic modulus	Density	Poisson's ratio
PU leather (20)	25MPa	1200kg/m^3	0.42
Skin (19)	60MPa	1020kg/m^3	0.4

Table 10: Material Properties

Cushion thickness was set as 5mm as lower thicknesses provided anomalistic stress values which could be due to issues with using a shell model in solidworks.

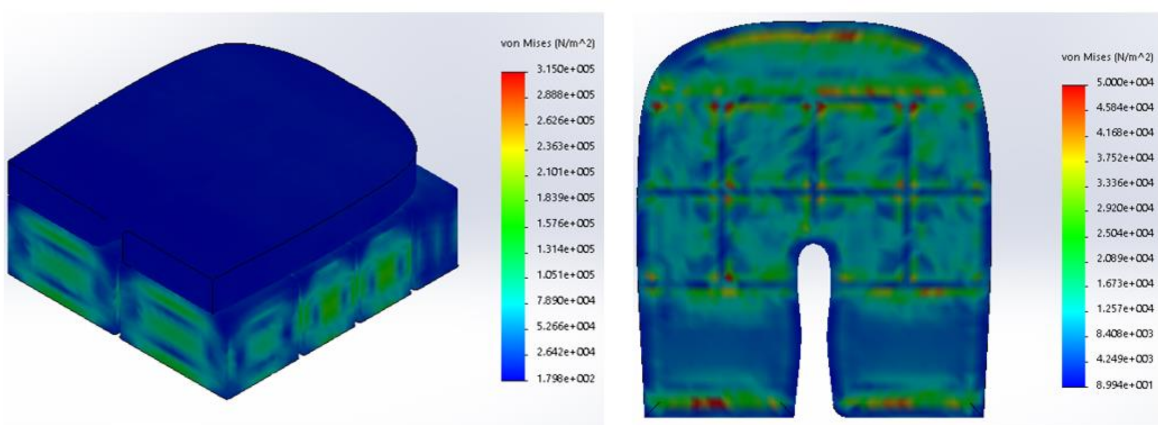


Figure 25: Stresses on the skin and cushion using the Shell model

Compared to the solid model, the shell model presents us with a more detailed and accurate analysis since the solid model assumes the cushion to act like foam making it unrealistic.

Mesh Convergence:

For our complete cushion shell model, mesh convergence was required in order to determine and ensure that the results of our analysis are not affected by altering the size of the mesh. This is done to confirm that our solution is converged.

The mesh size/Total elements are then compared against the maximum von mises stress in the cushion to study the trend.

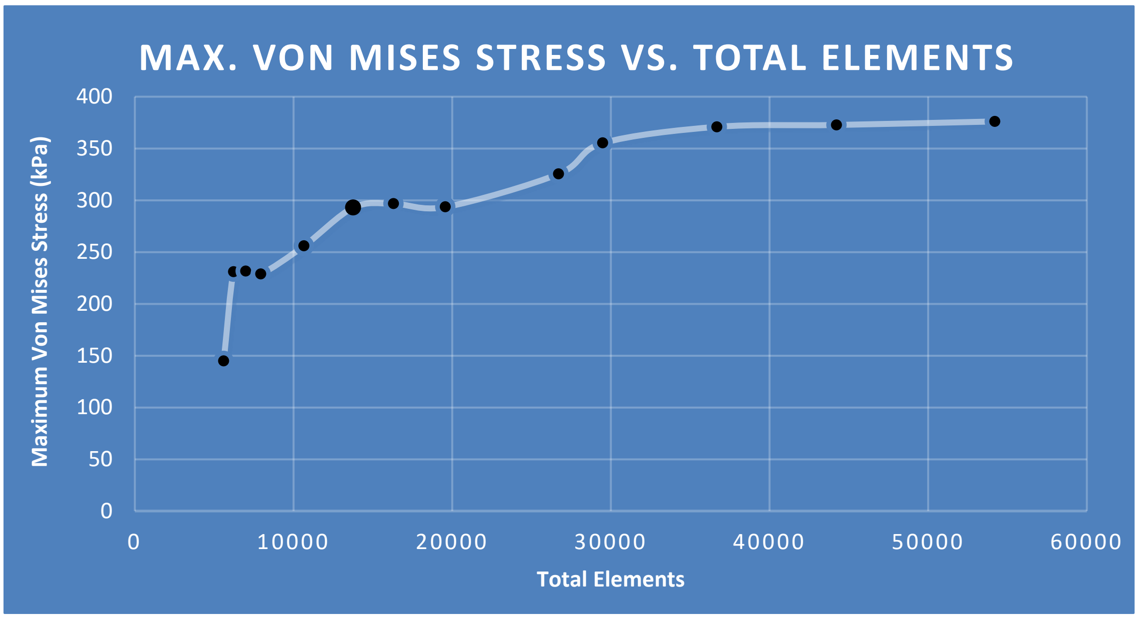


Figure 26: Maximum Von Mises Stress vs. total elements graph

- It can be observed from this graph that the solution for maximum von mises stress highly varies for total element numbers less than 30000. Thus, this analysis needs to be performed with mesh containing 30000 or more elements.
- Increasing the number of elements above 30000 will increase the accuracy by a small amount whereas the computation time could increase by a larger value.
- 30,000 elements are equal to a mesh size of **0.0162m**, thus by choosing a mesh size smaller than this value we ensure that our results are reliable.

CHAPTER 4: RESULTS AND DISCUSSIONS

Artefact Reduction:

Our previous analyses show pressure surges on the skin in regions where the skin is placed on the compartment spacings, thus creating artefacts on the skin. This phenomenon can be attributed with the rigid behavior of the shell structure and is something that might not appear in a practical structure manufactured with flexible PU leather. Nevertheless, we still aim to reduce these surges by applying the following theoretical approaches:

Approach #1: Eliminate any spaces between the compartments and remove the inner fillets on top of the cushion. This results in a cushion with a flat top while still maintaining the shell structure, this helps in reducing any surges happening due to the shearing at the spaces. The shell thickness towards the inside of the cushion doubles due to the merging of compartments.

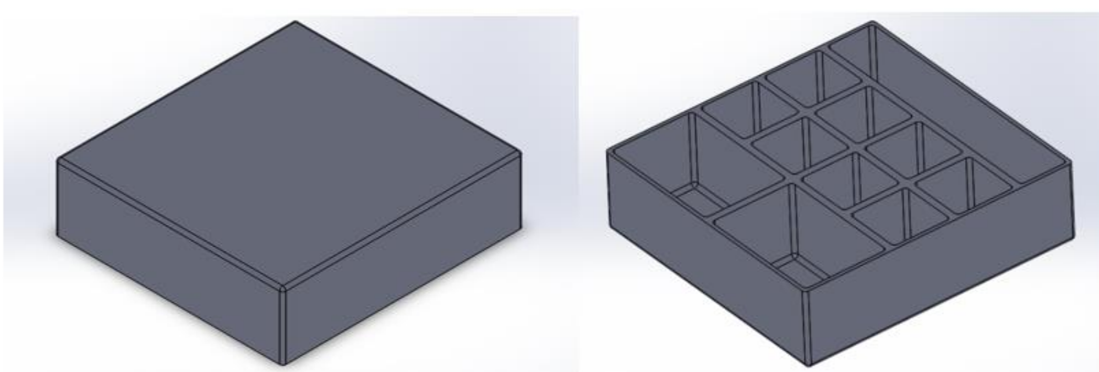


Figure 27: Isometric top (left) and bottom (right) views of approach #1

First Approach Results:

In the first approach we Eliminated any spaces between the compartments and remove the inner fillets on top of the cushion, resulting in a uniform, flat surface and observed the following results:

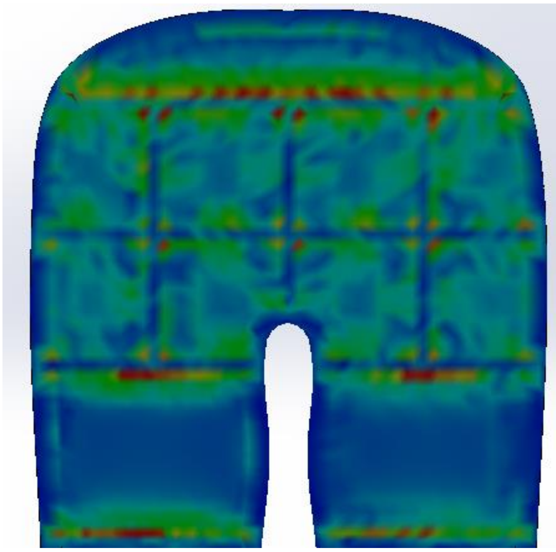


Figure 28: Original Reference

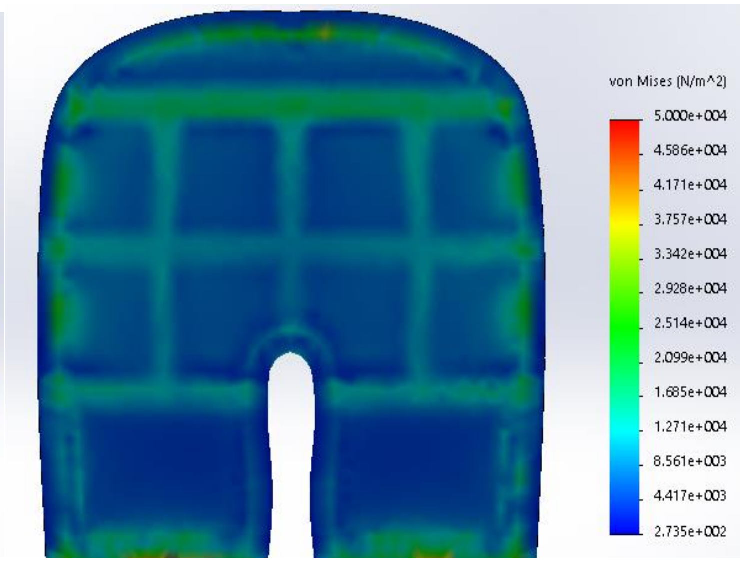


Figure 29: First Approach Results

As we can observe, there is a sharp decline in the prominence stress pattern we observed after applying our first approach.

Approach #2: Eliminate the spacing between the compartments but keep the inner fillets on top of the cushion intact. This allows us to carry out a more realistic approach compared to Approach #1. The merging of the compartments causes the internal compartment wall thickness to double like approach #1.

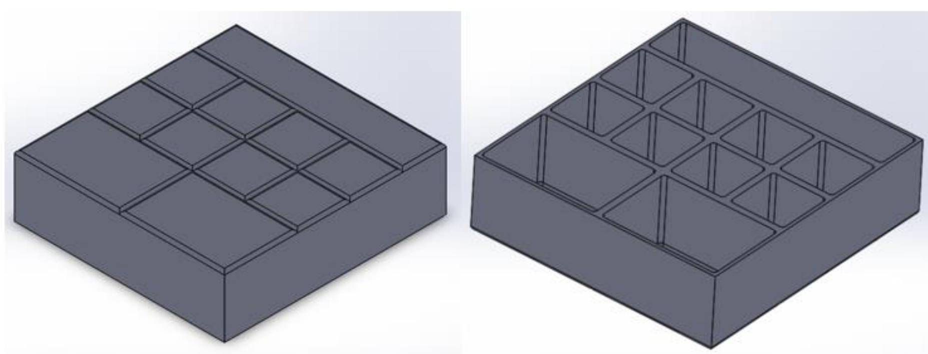


Figure 30: Isometric top (left) and bottom (right) views of approach #2

Second Approach Results:

In the second approach we eliminated the spacing between the compartments but keep the inner fillets on top of the cushion intact. and observed the following results:

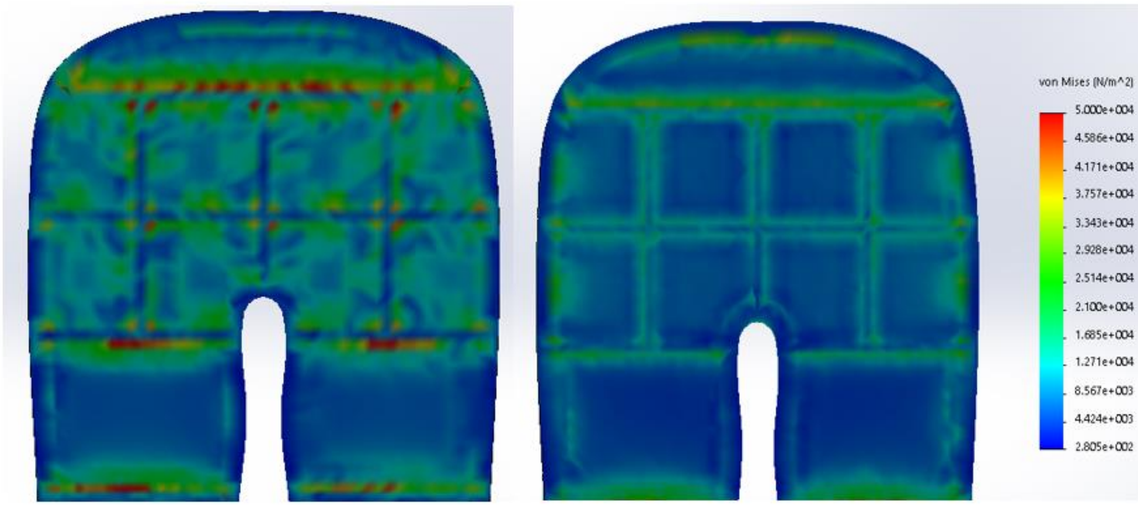


Figure 31: Original reference (left) and Second approach results (right)

Observation:

- Artefacts still appear; however, they produce significantly less stress when compared to the original analysis.
- Very slight increase in stress when compared to First Approach.
- Pressure surges occur less gradually when compared to First Approach.
- But the pattern if more prominent, the reason being the fillets on the top surface instead of a flat one, this factor slightly increases the prominence of the Artifacts.
- It is more realistic than the first approach and gives more accurate results.

Approach #3: This approach introduces a new component to the analysis, the seat cover, a single part made of the same and thickness as the cushion fabric. Using this cover allows us to obtain a flat top surface material without the need to eliminate compartment gaps, thus giving us a more realistic approach.

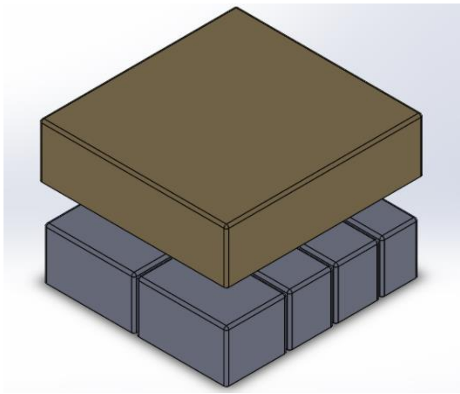


Figure 32: Exploded view of approach #3

In the third approach we introduce a new component to the analysis, the seat cover, a single part made of the same material and thickness as the cushion fabric and observed the following results:

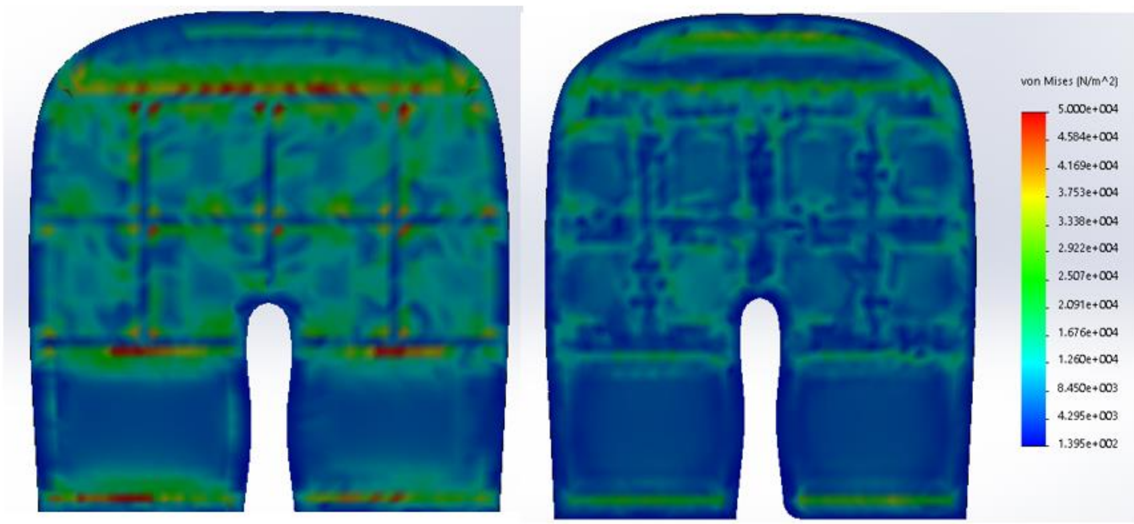


Figure 33: Original reference (left) and Second approach results (right)

Observation:

- Significant reduction in stress compared to original analysis.
- Gradual change in stress compared to original analysis.
- More realistic skin pressure data compared to the first two approaches.
- The third approach of analysis represents the actual real-life product we plan to develop, as the real-life product will have a seat cover installed as well.
- Hence the results and values observed in this case represent the data which be closer to product, and we will be using this approach in all the analysis and results that follow.

Comparison of approaches:

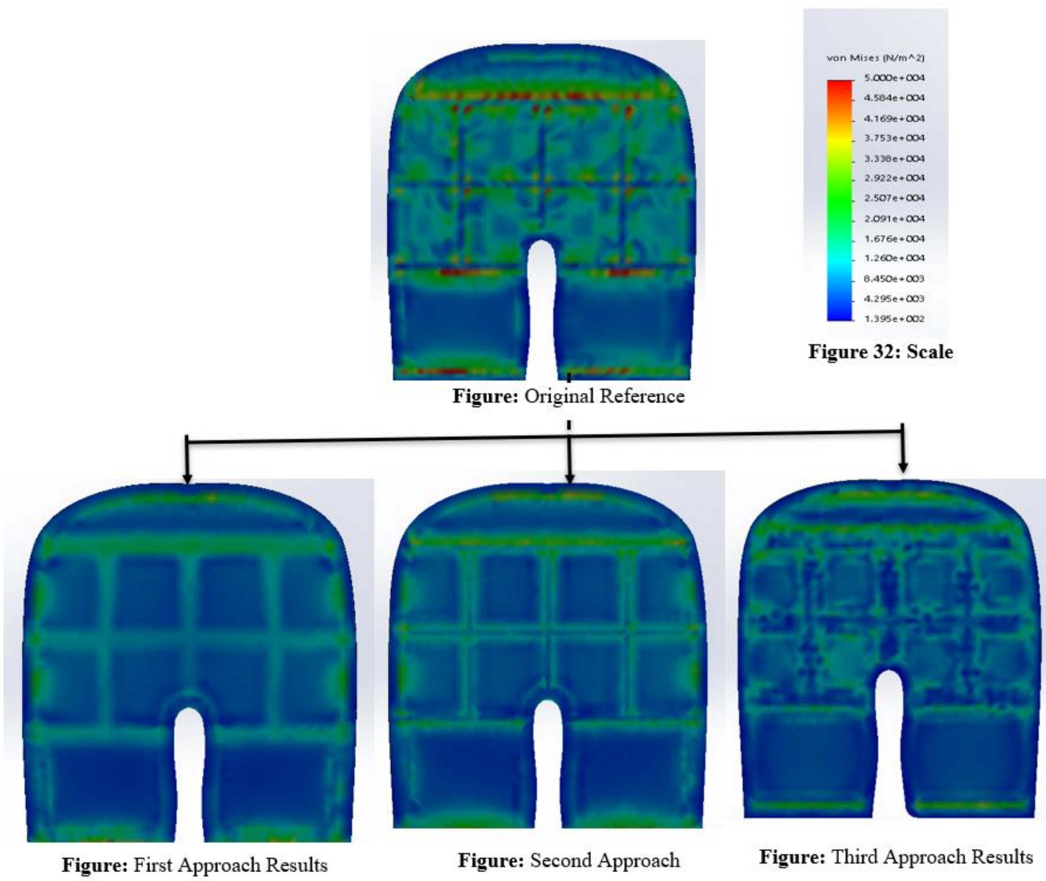


Figure 34: Comparison

Discussion:

The third approach gives us the most accurate and realistic results.

Now, the stress pattern we observe in our analysis is very different from the one displayed in the literature review, the reasons for this anomaly are:

- Instead of a flat-hard surface, we are using a compartmentalized cushion that is inflated by air pressure.
- The air inflated cushion provides a more unform weight distribution by increasing the skin contact area with the seat, resulting in a further stress reduction,
- The compartments can slide in all directions, as they are air inflated, this creates a very comfortable contour of the seat, which is very essential for both patients and healthy people.

Summary:

As we have observed, the third approach is the most realistic one and provides us the most accurate results as well, as for any further analysis, we will be sticking to the third approach and the cushion used will have a cover over it.

Even in real life application the product, when installed, will include a similar cover to keep the compartments and the cushion in a certain aligned shape and form, and this further justifies our use of the third approach.

Changing Pressure Parameters:

Now, our aim is to reduce the stress experienced by human skin and keep the patient safe from pressure ulcers as long as we can. There are two ways through which we can achieve this:

- *Reduce the stress level* below 30 mmHg, below this level, human skin does not develop pressure ulcers irrespective of the time for which it is applied.
- Increase the *skin perfusion*: Alternate the pressure in such a manner that it increases the *skin perfusion* and keeps the skin safe and ulcer free.

The first method is possible only in case of a bed, when the patient is laying down on the bed, but with a patient sitting on the wheelchair, the weight of the upper body makes it physically impossible to keep the pressures below 30 mmHg at all points of the skin/cushion contact, which leads us to the second approach, alternate the pressure experienced by skin and keep the patient safe.

Now that the approach has been decided, that will be alternating pressure to keep the skin safe, we accomplish this by reducing and increasing the air pressure inside certain selected compartments, this leads to a non-uniform load distribution and stress levels experienced by human skin keep changing, paving the way for skin perfusion and increased blood follow, resulting in prevention of pressure ulcers.

Pattern of Air Pressure Alteration:

Since we have two main user modes included in the Control:

- Preset Time Mode
- Feedback Mode

Preset mode:

In case of preset mode, the compartments will be inflating and deflating in a predefined manner, discussed earlier in the methodology as well.

Feedback Mode:

In case of feedback mode, the compartments will inflate and deflate according to the input received from the pressure sensors which is acting as the feedback for our Control System. Before we proceed to the results, let us look at the compartment configuration in this case.

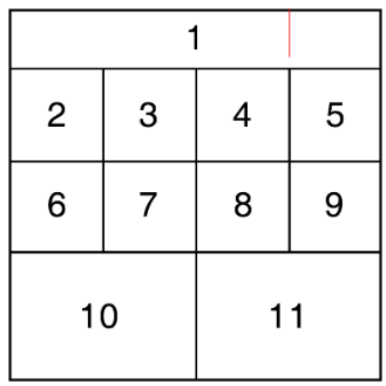


Figure 35: Compartment Configuration

Note: Since stress on lower body is viewed from beneath, the numbering will be mirrored across the vertical axis

Pressure Conditions:

Normal condition: All compartments are at their preset maximum air pressures.

Table 11: Pressure Table (Normal)

Compartment	Pressure (kPa)	Average skin Pressure (kPa)	Average skin pressure (mmHg)
1	1.960	12.736	95.529
2	4.138	7.261	54.462
3	4.138	8.167	61.258
4	4.138	7.924	59.435
5	4.138	7.339	55.047
6	4.138	6.503	48.776
7	4.138	6.959	52.197
8	4.138	6.860	51.454
9	4.138	6.566	49.249
10	1.960	5.730	42.978
11	1.960	5.747	43.106

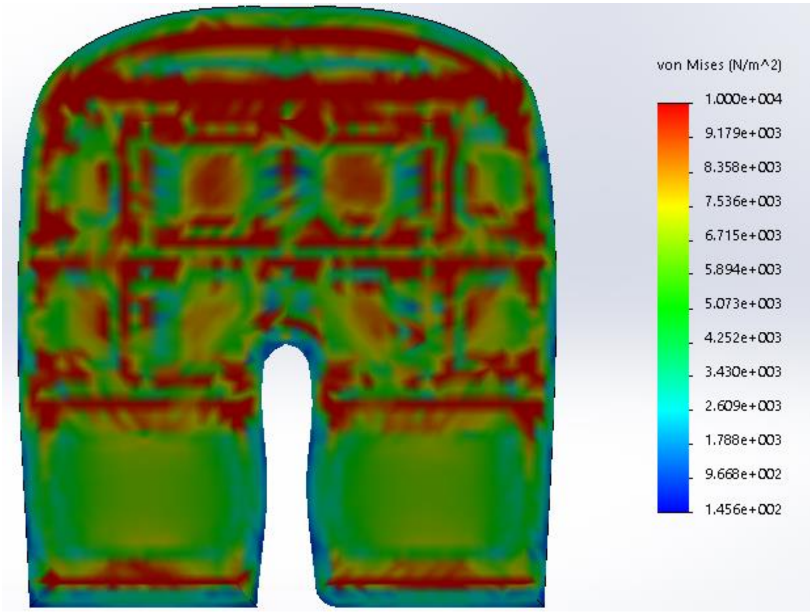


Figure 36: Map

Condition 1: We deflate just the 7th compartment and look at the results produced due to the deflation.

Table 12: Pressure table (7th deflated)

Compartment	Pressure (kPa)	Average Skin Pressure (kPa)	Average skin pressure (mmHg)
1	1.960	12.736	95.528
2	4.138	7.261	54.462
3	4.138	8.167	61.257
4	4.138	7.924	59.435
5	4.138	7.339	55.047
6	4.138	6.503	48.776
7	**2.500**	**5.955**	**44.666**
8	4.138	6.860	51.454
9	4.138	6.566	49.249
10	1.960	5.730	42.978
11	1.960	5.747	43.106

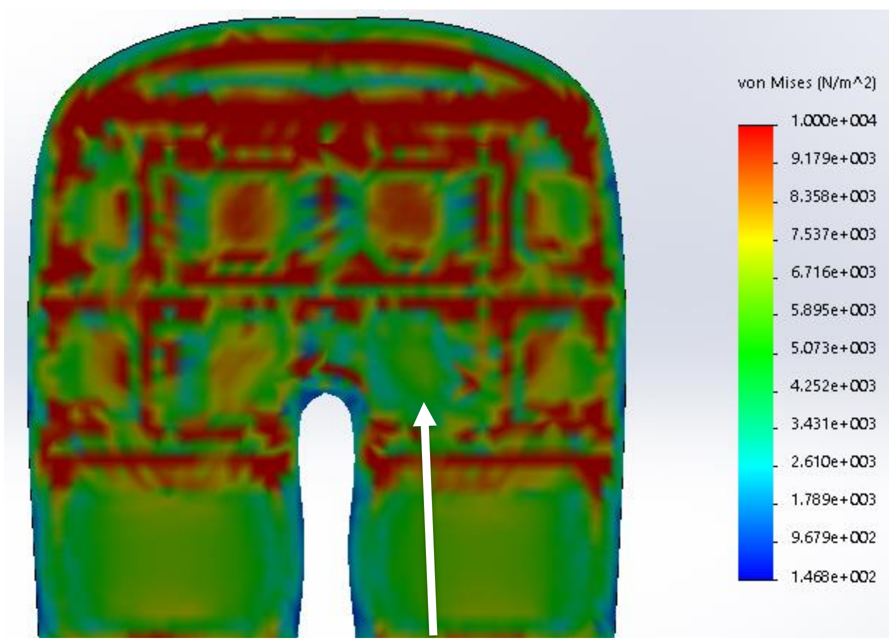


Figure 37: Compartment 7 is deflated

Condition 2: Defalted Compartments 2,5,7 and 8 and observed reduced stresses.

Table 13: Pressure table (2,5,7 and 8 deflated)

Compartment	Pressure (kPa)	Average skin Pressure (kPa)	Average skin pressure (mmHg)
1	1.960	12.795	95.97
2	2.500	6.738	**50.539**
3	4.138	8.129	60.972
4	4.138	7.902	59.27
5	**2.500**	6.738	**50.539**
6	4.138	6.613	49.602
7	2.500	5.967	**44.756**
8	2.500	5.812	**43.594**
9	4.138	6.542	49.069
10	1.960	5.754	43.158
11	1.960	5.747	43.106

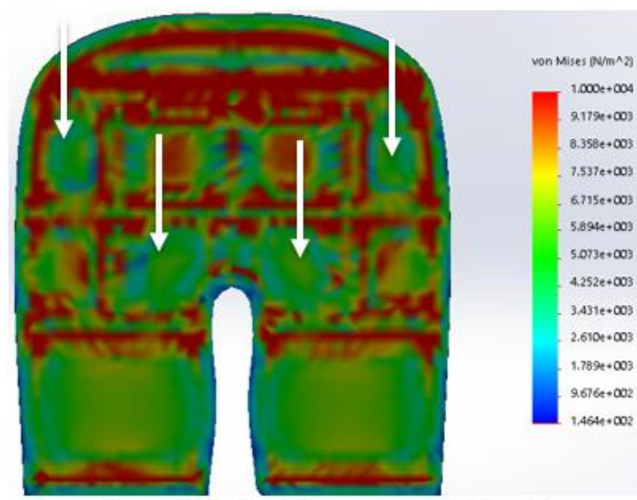


Figure 38: Deflated Compartments 2,5,7 and 8

Condition 3: Deflated 1,3,4,6 and 9 and observed similar results.

Table 14: Pressure table (2,5,7 and 8 deflated)

Compartment	Pressure (kPa)	Average skin Pressure (kPa)	Average skin pressure (mmHg)
1	0.980	11.415	**85.62**
2	4.138	7.293	54.702
3	2.500	7.385	**55.392**
4	2.500	7.152	**53.644**
5	4.138	7.358	55.19
6	2.500	5.943	**44.576**
7	4.138	7.042	52.819
8	4.138	6.949	52.122
9	2.500	5.908	**44.314**
10	1.960	5.743	43.076

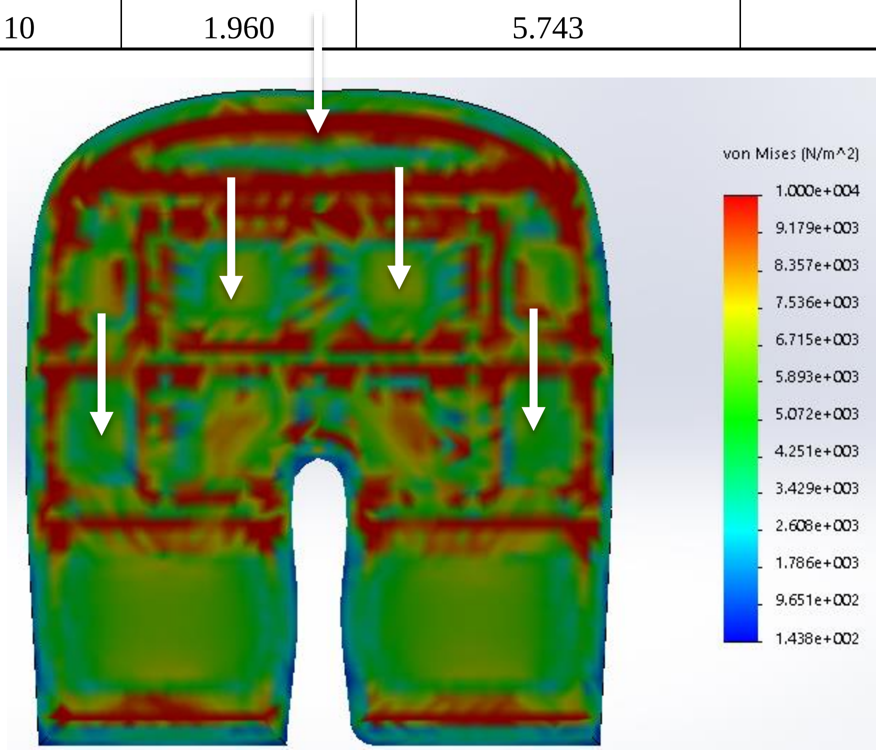


Figure 40: Deflated 1,3,4,6 and 9

Pressure Conditions Summary:

Normal loading condition

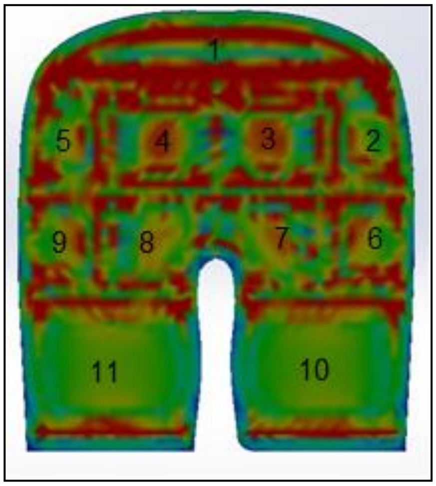


Figure 42: Normal

Deflate compartments 1,3,4,6 and 9.

Inflate compartments 1,3,4,6 and 9.

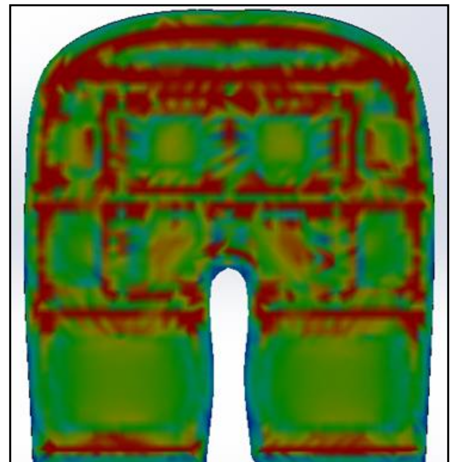
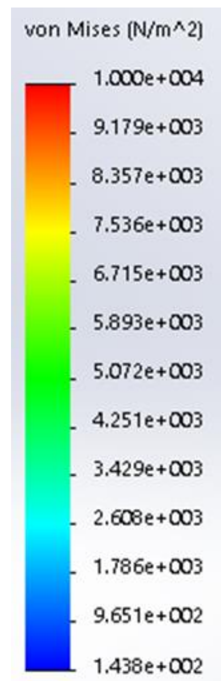


Figure 41: 1,3,4,6 and 9. Deflated



Inflate compartment 8.

Deflate compartment 8.

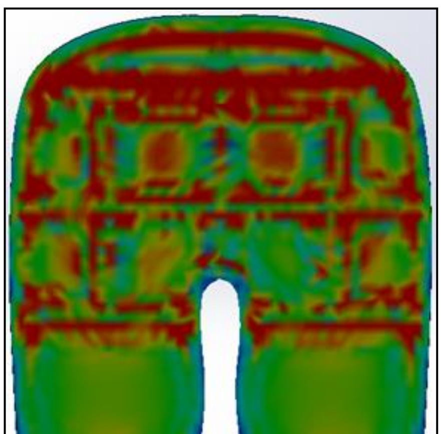


Figure 43: 7 Deflated

Inflate compartments 2,5 and 8.

Deflate compartments 2,5 and 8.

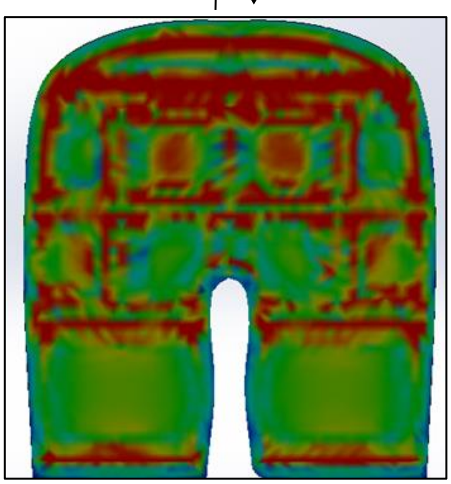


Figure 44: 2,5 and 8 deflated

Results:

- A direct correlation is observed between the change in pressure inside a compartment and the pressures observed on the skin.
- Deflating a compartment will lower the average skin pressure in that region and inflating will increase the average skin pressure.

Summary:

A direct correlation can be observed between the air pressure inside the compartment and the stress that is acting on the human skin, hence by reducing the internal compartment pressure, we can reduce the skin stresses but to a certain level, after that the shear produced due to the uneven pressures inside different compartments exceeds the reduction in the stress we achieve via the deflated compartment.

The continued inflation and deflation give us the required alternating pressures acting on the human skin and hence results in increased skin perfusion which in turn helps in prevention of pressure ulcers by keeping the tissues safe and healthy.

Complete Prototype model:

With the design and operating parameters finalized, Solidworks was used to render a complete prototype model of the finalized smart cushion.

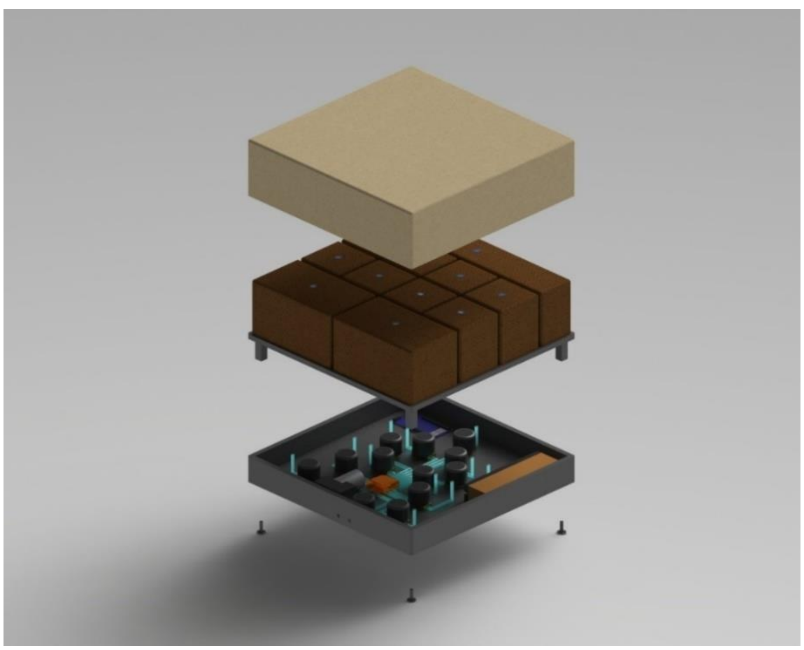


Figure 45: Complete Prototype model

CHAPTER 5: CONCLUSION AND RECOMMENDATION

Conclusion:

The following conclusions can be made from this project:

1. **Changing compartment pressure changes skin pressures.**

As stated in results section, the skin pressure can be changed by either decreasing the pressure applied or changing compartment pressures to allow skin perfusions. Since, the patient is immobile we change skin pressures by the latter approach. We change the pressure of each compartment in a timely manner with feedback to avoid high pressure points from developing. The results section further proves our method by showing the reduction in skin pressures when the internal pressure of the compartment is reduced by deflation. These compartments alternates pressures on different parts of the body in contact with cushion to allow skin perfusions and avoid unsafe pressures at a single point of the contact.

2. **The compartments beneath the hip bone are high priority zones.**

The pressure map displayed in our analysis in the results section show comparatively high pressures in the middle four compartments which lie beneath the hip bone in the normal sitting posture. These high-pressure compartments are areas of high concern so the pressures in these compartments are alternated at a higher frequency to avoid skin and tissue damage. The map shows these high-pressure zones using a color code with a reference at the side of it. The pressure map of a patient in our literature review validates the distribution we achieved using our methodology. Both the patient and software pressure distributions indicate comparatively high-pressure points beneath the hip bone. This validation helps us to reach this conclusion.

3. **PU Leather passes our material validation study.**

We checked the stresses on our cushion design when a patient sits on it and compared the von mises stresses with the specifications of the PU leather to perform our failure study. The Von mises stresses experienced in the cushion were well below the limits of the material. Moreover, PU leather is water, heat, cold, chemical and tear resistant and is flexible, comfortable, and repairable. These helps us to conclude that PU leather is the right material.

4. **Feedback from pressure sensors helps the cushion to allow skin perfusions.**

The feedback loop in our control system takes data from the pressure sensors and accordingly change pressures of the high-pressure compartments after a certain time. This allows skin perfusions as supported by the analysis in our results section of the report. Alternating compartment pressures alternates the skin pressures, which in turn allows blood flow in the lower part of the body avoiding any injuries to the skin or tissue muscle.

5. **Artifact reduction achieved by the methods discussed.**

Artifacts in our analysis were reduced considerably by the three approaches discussed in the results section of our report. They were most considerably removed by the third approach which is by covering the cushion with a seat cover. This represents the most accurate model as compared to the cushion which will be manufactured. Hence the data represented by this approach more accurately describes the pressures which will be experienced by the actual cushion. The artifacts are due to software inadequacy of performing analysis on a shell structure. By placing the cover, the pressure is more accurately distributed, and artifacts are considerably removed from the results.

Recommendation:

1. **Ergonomically designed for commercial use.**

The cushion can be further used for office workers, drivers and pilots who must sit at a single place for long periods of time. Sitting in a constant posture for unsafe periods of time develops pressure sores on the lower part of the body. The cushion will enable people from these and similar professions to avoid pressure ulcers. Furthermore, the cushion will allow skin perfusions to make sure the blood flow in the lower part of the body is maintained. The cushion can be commercially used in shops, homes, and cars where people have a risk of developing this skin condition. The portability of the cushion will help the consumer to carry it around and use it anywhere. Moreover, due to the global pandemic the offices are encouraging employees to work from home which has made people sit at a single place for unsafe periods of time. So, this cushion will provide a solution for these people to avoid pressure ulcers.

2. **Cushion design can be extrapolated to form a smart bed.**

This cushion for wheelchair can be extrapolated to form a smart mattress with greater number of compartments. This mattress will help the bed-ridden patients to avoid developing pressure ulcers. The smart mattress will take feedback from the pressure sensors installed across the surface and change the compartment pressures according to the values obtained. The mattress can be used for hospital beds and nursing homes for the old age people. This will enable nurses to perform less frequent adjustments to the postures of the patients and will make the users feel safer.

3. **Both global and local markets can be targeted.**

The product can be targeted to global market as well since the available products offer less functionality and are very expensive. At the same time, smart mattress can also be targeted towards both global and local markets. The cushion can be further integrated into

Pakistan's health care system to provide admitted patients with them. The project can be further extended in future to provide the cushion to more countries' health care systems.

4. **Better Analysis**

Better approach would be to manufacture a fully working prototype and perform analysis on the prototype to improve results. The material durability and load bearing capabilities of the cushion will be better judged better by a working prototype. So, it is recommended for future to perform these analyses.

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APPENDIX I: CODE

Code for Preset mode

```
void setup() {

pinMode (3,OUTPUT); //Valves
pinMode (4,OUTPUT);
pinMode (5,OUTPUT);
pinMode (6,OUTPUT);
pinMode (7,OUTPUT);
pinMode (8,OUTPUT);
pinMode (9,OUTPUT);
pinMode (10,OUTPUT);
pinMode (11,OUTPUT);
pinMode (12,OUTPUT);
pinMode (13,OUTPUT);
pinMode (14,OUTPUT); //Exhaust Valve
pinMode (15,OUTPUT); //Pump
pinMode (16,OUTPUT); //LED

void loop(){

delay (300000);

digitalWrite (5,LOW);  //Deflate
compartments 3,4,7,8
digitalWrite (6,LOW);
digitalWrite (9,LOW);
digitalWrite (10,LOW);
digitalWrite (14,LOW);

delay (5000);

digitalWrite (5;HIGH);
digitalWrite (6,HIGH);
digitalWrite (9,HIGH);
digitalWrite (10,HIGH);
digitalWrite (14,HIGH);

delay (30000);


digitalWrite (5,LOW); //Inflate
compartments 3,4,7,8
digitalWrite (6,LOW);
digitalWrite (9,LOW);
digitalWrite (10,LOW);
digitalWrite (15,LOW);

delay (5000);

digitalWrite (5,HIGH);
digitalWrite (6,HIGH);
digitalWrite (9,HIGH);
digitalWrite (10,HIGH);
digitalWrite (15,HIGH);

delay (300000);

digitalWrite (4,LOW); //deflate
compartments 2,5,6,9
digitalWrite (7,LOW);
digitalWrite (8,LOW);
digitalWrite (11,LOW);
digitalWrite (14,LOW);

delay (5000);

digitalWrite (4,HIGH);
digitalWrite (7,HIGH);
digitalWrite (8,HIGH);
digitalWrite (11,HIGH);
digitalWrite (14,HIGH);

delay (30000);

digitalWrite (4,LOW); //inflate
compartments 2,5,6,9
digitalWrite (7,LOW);
digitalWrite (8,LOW);
digitalWrite (11,LOW);
digitalWrite (15,LOW);

delay (5000);

digitalWrite (4,HIGH);
digitalWrite (7,HIGH);
digitalWrite (8,HIGH);
digitalWrite (11,HIGH);
```

```
digitalWrite (15,HIGH);

delay (300000);

digitalWrite (3,LOW); //Deflate
compartments 1,10,11
digitalWrite (12,LOW);
digitalWrite (13,LOW);
digitalWrite (14,LOW);

delay (5000);

digitalWrite (3,HIGH);
digitalWrite (12,HIGH);
digitalWrite (13,HIGH);
digitalWrite (14,HIGH);

delay (30000);

digitalWrite (3,LOW);  //Inflate
compartments 1,10,11
digitalWrite (12,LOW);
digitalWrite (13,LOW);
digitalWrite (15,LOW);

delay (5000);

digitalWrite (3,HIGH);
digitalWrite (12,HIGH);
digitalWrite (13,HIGH);
digitalWrite (15,HIGH);

}
```

Code for Feedback mode

```
int fsrPin = 0; // the FSR and 10K
pulldown are connected to a0
int fsrPin2 = 1;
int fsrPin3 = 2;
int fsrPin4 = 3;
int fsrPin5 = 4;
int fsrPin6 = 5;
int fsrPin7 = 6;
int fsrPin8 = 7;
int fsrPin9 = 8;
int fsrPin10 = 9;
int fsrPin11 = 10;

int fsrReading;     // the analog reading
from the FSR resistor divider
int fsrReading2;
int fsrReading3;
int fsrReading4;
int fsrReading5;
int fsrReading6;
int fsrReading7;
int fsrReading8;
int fsrReading9;
int fsrReading10;
int fsrReading11;

int C1S = 0;
int C2S = 0;
int C3S = 0;
int C4S = 0;
int C5S = 0;
int C6S = 0;
int C7S = 0;
int C8S = 0;
int C9S = 0;
int C10S = 0;
int C11S = 0;

int C1M = 0;
int C2M = 0;
int C3M = 0;
int C4M = 0;
int C5M = 0;
int C6M = 0;
int C7M = 0;
int C8M = 0;
int C9M = 0;
int C10M = 0;
int C11M = 0;

int C1H = 0;
int C2H = 0;
int C3H = 0;
int C4H = 0;
int C5H = 0;
int C6H = 0;
```

```
int C7H = 0;
int C8H = 0;
int C9H = 0;
int C10H = 0;
int C11H = 0;

int alternator = 0;
void setup() {

pinMode (3,OUTPUT); //Valves
pinMode (4,OUTPUT);
pinMode (5,OUTPUT);
pinMode (6,OUTPUT);
pinMode (7,OUTPUT);
pinMode (8,OUTPUT);
pinMode (9,OUTPUT);
pinMode (10,OUTPUT);
pinMode (11,OUTPUT);
pinMode (12,OUTPUT);
pinMode (13,OUTPUT);
pinMode (14,OUTPUT); //Exhaust Valve
pinMode (15,OUTPUT); //Pump
pinMode (16,OUTPUT); //LED

digitalWrite (7,HIGH);
digitalWrite (6,HIGH);
digitalWrite (5,HIGH);
digitalWrite (3,LOW);
digitalWrite (4,HIGH);
delay(3000);
digitalWrite (6,LOW);
delay(20000);
digitalWrite (3,HIGH);
digitalWrite (4,LOW);
delay(20000);
digitalWrite (4,HIGH);
digitalWrite (5,HIGH);
digitalWrite (6, HIGH);

delay (5000);

}

void loop() {

  fsrReading = analogRead(fsrPin);
  fsrReading3 = analogRead(fsrPin3);
  fsrReading4 = analogRead(fsrPin4);
  fsrReading5 = analogRead(fsrPin5);
  fsrReading6 = analogRead(fsrPin6);
  fsrReading7 = analogRead(fsrPin7);
  fsrReading8 = analogRead(fsrPin8);
  fsrReading9 = analogRead(fsrPin9);
  fsrReading10 = analogRead(fsrPin10);
  fsrReading11 = analogRead(fsrPin11);

if (alternator == 0){
//Changes value of alternator for inflation or deflation of low pressure compartments.
  alternator = 1;
 }
 else {
  alternator = 0;
 }

if (alternator == 1){
  lowdeflate();
}
else {
  lowinflate();
}

delay(5000);
  mediumdeflate();

delay(5000);
  highdeflate();

delay(5000);
  highinflate();

delay(5000);
  mediuminflate();

delay(5000);
  highdeflate();

delay(5000);
  highinflate();

delay(5000);
  mediumdeflate();
delay(5000);
  highdeflate();

delay(5000);
  highinflate();
```

```
delay(5000);
  mediuminflate();

delay(5000);
}

void lowdeflate(){
//Deflates low pressure compartment.
   if ( 100 < fsrReading && fsrReading <
500 ){        //Tests low pressure
condition.
   C1S = 1;
//Assigns value of 1 to identify
compartment deflated.
   digitalWrite (3, LOW);
//Opens valve for compartment 1.
   digitalWrite (14, LOW);
//Opens exhaust valve.
   delay(5000);
   digitalWrite (3, HIGH);
//Closes valve for compartment 1.
   digitalWrite (14, HIGH);
//Closes exhaust valve.
   }
 if ( 100 < fsrReading2 && fsrReading2 <
500 ){
   C2S = 1;
//Assigns value of 1 to identify
compartment deflated.
   digitalWrite (4, LOW);
//Opens valve for compartment 2.
   digitalWrite (14, LOW);
//Opens exhaust valve.
   delay(5000);
   digitalWrite (4, HIGH);
//Closes valve for compartment 2.
   digitalWrite (14, HIGH);
//Closes exhaust valve.
   }
 if ( 100 < fsrReading3 && fsrReading3 <
500 ){
   C3S = 1;
   digitalWrite (5, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (5, HIGH);
   digitalWrite (14, HIGH);
 }
  if ( 100 < fsrReading4 && fsrReading4 <
500 ){
   C4S = 1;
   digitalWrite (6, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (6, HIGH);
   digitalWrite (14, HIGH);
   }
  if ( 100 < fsrReading5 && fsrReading5 <
500 ){
   C5S = 1;
   digitalWrite (7, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (7, HIGH);
   digitalWrite (14, HIGH);
   }
  if ( 100 < fsrReading6 && fsrReading6 <
500 ){
   C6S = 1;
   digitalWrite (8, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (8, HIGH);
   digitalWrite (14, HIGH);
   }
   if ( 100 < fsrReading7 && fsrReading7
< 500 ){
   C7S = 1;
   digitalWrite (9, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (9, HIGH);
   digitalWrite (14, HIGH);
   }
   if ( 100 < fsrReading8 && fsrReading8
< 500 ){
   C8S = 1;
   digitalWrite (10, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (10, HIGH);
   digitalWrite (14, HIGH);
   }
   if ( 100 < fsrReading9 && fsrReading9
< 500 ){
   C9S = 1;
   digitalWrite (11, LOW);
```

```
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (11, HIGH);
   digitalWrite (14, HIGH);
   }
   if ( 100 < fsrReading10 &&
fsrReading10 < 500 ){
   C10S = 1;
   digitalWrite (12, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (12, HIGH);
   digitalWrite (14, HIGH);
   }
   if ( 100 < fsrReading11 &&
fsrReading11 < 500 ){
   C11S = 1;
   digitalWrite (13, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (13, HIGH);
   digitalWrite (14, HIGH);
  }
}

void lowinflate(){
//Inflates low pressure compartment.
  if (C1S == 1){
//Checks if the compartment was
deflated previously.
   C1S = 0;
   digitalWrite (3, LOW);
 //Opens valve for compartment 1.
   digitalWrite (14, HIGH);
 //Closes exhaust valve.
   digitalWrite (15, LOW);
//Turns on the air pump.
   delay(10000);
   digitalWrite (14, HIGH);
//Closes valve for compartment 1.
   digitalWrite (15, HIGH);
//Turns off the air pump.
   }
if ( C2S == 1 ){
  C2S = 0;
   digitalWrite (4, LOW);
//Opens valve for compartment 2.
   digitalWrite (14, HIGH);
 //Closes exhaust valve.
   digitalWrite (15, LOW);
//Turns on the air pump.
   delay(10000);
   digitalWrite (4, HIGH);
 //Closes valve for compartment 2.
   digitalWrite (15, HIGH);
//Turns off the air pump.
   }
if ( C3S == 1 ){
  C3S = 0;
   digitalWrite (5, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (5, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C4S == 1 ){
  C4S = 0;
   digitalWrite (6, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (6, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C5S == 1 ){
  C5S = 0;
   digitalWrite (7, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (7, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C6S == 1 ){
  C6S = 0;
   digitalWrite (8, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (8, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C7S == 1 ){
  C7S = 0;
   digitalWrite (9, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
```

```
    delay(10000);
    digitalWrite (9, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C8S == 1 ){
   C8S = 0;
    digitalWrite (10, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (10, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C9S == 1 ){
   C9S = 0;
    digitalWrite (11, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (11, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C10S == 1 ){
   C10S = 0;
    digitalWrite (12, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (12, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C11S == 1 ){
   C11S = 0;
    digitalWrite (13, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (13, HIGH);
    digitalWrite (15, HIGH);
    }
  }

void mediumdeflate (){

  fsrReading = analogRead(fsrPin);
  fsrReading3 = analogRead(fsrPin3);
  fsrReading4 = analogRead(fsrPin4);
  fsrReading5 = analogRead(fsrPin5);
  fsrReading6 = analogRead(fsrPin6);
  fsrReading7 = analogRead(fsrPin7);
  fsrReading8 = analogRead(fsrPin8);
  fsrReading9 = analogRead(fsrPin9);
  fsrReading10 = analogRead(fsrPin10);
  fsrReading11 = analogRead(fsrPin11);

  if ( 500 < fsrReading && fsrReading <
800 ){
    if( C1S == 1 ){
      C1S = 0;
      C1M = 1;
      }
 else (){
    C1M = 1;
    digitalWrite (3, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (3, HIGH);
    digitalWrite (14, HIGH);
 }
    }
 if ( 500 < fsrReading2 && fsrReading2 <
800 ){
   if( C2S == 1 ){
      C2S = 0;
      C2M = 1;
      }
 else(){
    C2M = 1;
    digitalWrite (4, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (4, HIGH);
    digitalWrite (14, HIGH);
 }
    }
 if ( 500 < fsrReading3 && fsrReading3 <
800 ){
   if( C3S == 1 ){
      C3S = 0;
      C3M = 1;
      }
   else(){
    C3M = 1;
    digitalWrite (5, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (5, HIGH);
    digitalWrite (14, HIGH);
```

```
  }
 }
  if ( 500 < fsrReading4 && fsrReading4 <
800 ){
     if( C4S == 1 ){
      C4S = 0;
      C4M = 1;
      }
   else (){
    C4M = 1;
    digitalWrite (6, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (6, HIGH);
    digitalWrite (14, HIGH);
   }
    }
   if ( 500 < fsrReading5 && fsrReading5 <
800 ){
     if( C5S == 1 ){
      C5S = 0;
      C5M = 1;
      }
   else(){
    C5M = 1;
    digitalWrite (7, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (7, HIGH);
    digitalWrite (14, HIGH);
   }
    }
   if ( 500 < fsrReading6 && fsrReading6 <
800 ){
     if( C6S == 1 ){
      C6S = 0;
      C6M = 1;
      }
   else(){
    C6M = 1;
    digitalWrite (8, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (8, HIGH);
    digitalWrite (14, HIGH);
   }
    }
    if ( 500 < fsrReading7 && fsrReading7
< 800 ){
     if( C7S == 1 ){
      C7S = 0;
      C7M = 1;
      }
    else(){
    C7M = 1;
    digitalWrite (9, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (9, HIGH);
    digitalWrite (14, HIGH);
    }
    }
    if ( 500 < fsrReading8 && fsrReading8
< 800 ){
       if( C8S == 1 ){
      C8S = 0;
      C8M = 1;
      }
    else(){
    C8M = 1;
    digitalWrite (10, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (10, HIGH);
    digitalWrite (14, HIGH);
    }
    }
    if ( 500 < fsrReading9 && fsrReading9
< 800 ){
      if( C8S == 1 ){
      C8S = 0;
      C8M = 1;
      }
    else(){
    C9M = 1;
    digitalWrite (11, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (11, HIGH);
    digitalWrite (14, HIGH);
    }
    }
    if ( 500 < fsrReading10 &&
fsrReading10 < 800 ){
     if( C10S == 1 ){
      C10S = 0;
      C10M = 1;
      }
```

```
   else(){
   C10M = 1;
   digitalWrite (12, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (12, HIGH);
   digitalWrite (14, HIGH);
   }
   }
   if ( 500 < fsrReading11 &&
fsrReading11 < 800 ){
    if( C11S == 1 ){
     C11S = 0;
     C11M = 1;
     }
   else(){
   C11M = 1;
   digitalWrite (13, LOW);
   digitalWrite (14, LOW);
   delay(5000);
   digitalWrite (13, HIGH);
   digitalWrite (14, HIGH);
   }
  }
 }

void mediuminflate(){
 if (C1M == 1){
   C1M = 0;
   digitalWrite (3, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (14, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C2M == 1 ){
  C2M = 0;
   digitalWrite (4, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (4, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C3M == 1 ){
  C3M = 0;
   digitalWrite (5, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (5, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C4M == 1 ){
  C4M = 0;
   digitalWrite (6, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (6, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C5M == 1 ){
  C5M = 0;
   digitalWrite (7, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (7, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C6M == 1 ){
  C6M = 0;
   digitalWrite (8, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (8, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C7M == 1 ){
  C7M = 0;
   digitalWrite (9, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (9, HIGH);
   digitalWrite (15, HIGH);
   }
if ( C8M == 1 ){
  C8M = 0;
   digitalWrite (10, LOW);
   digitalWrite (14, HIGH);
   digitalWrite (15, LOW);
   delay(10000);
   digitalWrite (10, HIGH);
   digitalWrite (15, HIGH);
```

```
    }
if ( C9H == 1 ){
   C9H = 0;
    digitalWrite (11, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (11, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C10M == 1 ){
   C10M = 0;
    digitalWrite (12, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (12, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C11M == 1 ){
   C11M = 0;
    digitalWrite (13, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (13, HIGH);
    digitalWrite (15, HIGH);
    }

  }

void highdeflate(){

  fsrReading = analogRead(fsrPin);
  fsrReading3 = analogRead(fsrPin3);
  fsrReading4 = analogRead(fsrPin4);
  fsrReading5 = analogRead(fsrPin5);
  fsrReading6 = analogRead(fsrPin6);
  fsrReading7 = analogRead(fsrPin7);
  fsrReading8 = analogRead(fsrPin8);
  fsrReading9 = analogRead(fsrPin9);
  fsrReading10 = analogRead(fsrPin10);
  fsrReading11 = analogRead(fsrPin11);

  if ( 800 < fsrReading ){
if ( C1S == 1 ){
  C1S = 0;
  C1H = 1;
  }
if ( C1M == 1 ){
  C1M = 0;
  C1H = 1;
  }
if (C1H == 0 ){
    C1H = 1;
    digitalWrite (3, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (3, HIGH);
    digitalWrite (14, HIGH);
}
 }
    }
 if ( 800 < fsrReading2 ){
  if ( C2S == 1 ){
  C2S = 0;
  C2H = 1;
  }
if ( C2M == 1 ){
  C2M = 0;
  C2H = 1;
  }
if (C2H == 0 ){
    C2H = 1;
    digitalWrite (4, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (4, HIGH);
    digitalWrite (14, HIGH);
}
    }
 if ( 800 < fsrReading3 ){
  if ( C3S == 1 ){
  C3S = 0;
  C3H = 1;
  }
if ( C3M == 1 ){
  C3M = 0;
  C3H = 1;
  }
if (C3H == 0 ){
    C3H = 1;
    digitalWrite (5, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (5, HIGH);
    digitalWrite (14, HIGH);
}
```

```
 }
  if ( 800 < fsrReading4 ){
    if ( C4S == 1 ){
  C4S = 0;
  C4H = 1;
  }
if ( C4M == 1 ){
  C4M = 0;
  C4H = 1;
  }
if (C4H == 0 ){
    C4H = 1;
    digitalWrite (6, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (6, HIGH);
    digitalWrite (14, HIGH);
}
    }
   if ( 800 < fsrReading5 ){
    if ( C5S == 1 ){
  C5S = 0;
  C5H = 1;
  }
if ( C5M == 1 ){
  C5M = 0;
  C5H = 1;
  }
if (C5H == 0 ){
    C5H = 1;
    digitalWrite (7, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (7, HIGH);
    digitalWrite (14, HIGH);
}
    }
   if ( 800 < fsrReading6 ){
    if ( C6S == 1 ){
  C6S = 0;
  C6H = 1;
  }
if ( C6M == 1 ){
  C6M = 0;
  C6H = 1;
  }
if (C6H == 0 ){
    C6H = 1;
    digitalWrite (8, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (8, HIGH);
    digitalWrite (14, HIGH);
}
    }
    if ( 800 < fsrReading7 ){
      if ( C7S == 1 ){
  C7S = 0;
  C7H = 1;
  }
if ( C7M == 1 ){
  C7M = 0;
  C7H = 1;
  }
if (C7H == 0 ){
    C7H = 1;
    digitalWrite (9, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (9, HIGH);
    digitalWrite (14, HIGH);
}
    }
    if ( 800 < fsrReading8 ){
      if ( C8S == 1 ){
  C8S = 0;
  C8H = 1;
  }
if ( C8M == 1 ){
  C8M = 0;
  C8H = 1;
  }
if (C8H == 0 ){
    C8M = 1;
    digitalWrite (10, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (10, HIGH);
    digitalWrite (14, HIGH);
}
    }
    if ( 800 < fsrReading9 ){
     if ( C9S == 1 ){
  C9S = 0;
  C9H = 1;
  }
if ( C9M == 1 ){
  C9M = 0;
```

```
  C9H = 1;
  }
if (C9H == 0 ){
    C9H = 1;
    digitalWrite (11, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (11, HIGH);
    digitalWrite (14, HIGH);
}
    }
    if ( 800 < fsrReading10 ){
    if ( C10S == 1 ){
  C10S = 0;
  C10H = 1;
  }
if ( C10M == 1 ){
  C10M = 0;
  C10H = 1;
  }
if (C10H == 0 ){
    C10H = 1;
    digitalWrite (12, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (12, HIGH);
    digitalWrite (14, HIGH);
}
    }
    if ( 800 < fsrReading11 ){
      if ( C11S == 1 ){
  C11S = 0;
  C11H = 1;
  }
if ( C11M == 1 ){
  C11M = 0;
  C11H = 1;
  }
if (C11H == 0 ){
    C11H = 1;
    digitalWrite (13, LOW);
    digitalWrite (14, LOW);
    delay(5000);
    digitalWrite (13, HIGH);
    digitalWrite (14, HIGH);
   }
  }

void highinflate(){
if (C1H == 1){
    C1H = 0;
    digitalWrite (3, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (14, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C2H == 1 ){
   C2H = 0;
    digitalWrite (4, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (4, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C3H == 1 ){
   C3H = 0;
    digitalWrite (5, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (5, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C4H == 1 ){
   C4H = 0;
    digitalWrite (6, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (6, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C5H == 1 ){
   C5H = 0;
    digitalWrite (7, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (7, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C6H == 1 ){
   C6H = 0;
    digitalWrite (8, LOW);
    digitalWrite (14, HIGH);
```

```
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (8, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C7H == 1 ){
   C7H = 0;
    digitalWrite (9, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (9, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C8H == 1 ){
   C8H = 0;
    digitalWrite (10, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (10, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C9H == 1 ){
   C9H = 0;
    digitalWrite (11, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (11, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C10H == 1 ){
   C10H = 0;
    digitalWrite (12, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (12, HIGH);
    digitalWrite (15, HIGH);
    }
if ( C11H == 1 ){
   C11H = 0;
    digitalWrite (13, LOW);
    digitalWrite (14, HIGH);
    digitalWrite (15, LOW);
    delay(10000);
    digitalWrite (13, HIGH);
    digitalWrite (15, HIGH);
    }
 }
```

APPENDIX II: PROOF OF CONCEPT DEMO

Preset mode:

https://drive.google.com/file/d/1-0EvUGyqmL97vc1QwY995oQ5nyTny3Aa/view?usp=sharing

Feedback mode:

https://drive.google.com/file/d/1-c9uWTEnAvUfPHzDRv-gyF5S3IKlhkiV/view?usp=sharing

Four-Compartment Feedback mode:

https://drive.google.com/file/d/113Y1EtcGzeM4hCUFzZ5w57mtQgkL6zWL/view?usp=sharing