FleXo – Flexible Exoskeleton for Therapeutic Use

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MSc Report

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1 INTRODUCTION

FleXo- Flexible exoskeleton for therapeutic use, was a WEAR Sustain funded project initiated by bio-media designer company, Sensoree [1] in collaboration with University of Twente. WEAR (Wearable Technologists Engage with Artists for Responsible Innovation) Sustain [2] is a Horizon 2020 research and innovation initiative funded by the European Commission to engage sustainable cross-disciplinary wearable technologies and smart textiles as one of the main objectives. The idea of FleXo was inspired from the previous projects by Sensoree that detect and imitate the feeling of Awe; briefly discussed in section 2.2.

The main research question that guides this project is, how to realize a system that can mediate touch for the use in physiotherapy. Touch is the main basic element that has been used by physiotherapists and they use 33 different combinations of touch depending on the therapy [1], [2]; and is called as mediated touch when the feeling is imitated using a device. Haptic technology had made this possible and a review by Haans [3] gives an overview of mediated social touch citing existing systems for touch events like hugging, hand-holding, pokes, handshakes and so on. A pilot study was conducted by Huisman [4] to understand how people experience mediated touch and it has been noted that the mediated touch is influenced by many factors such as cultural, interpersonal relationship, gender and the body area used.

As the primary focus is for the use in physiotherapy, the intended design should provide mediated touch in the form of pressure on the body and it can be realized using soft robotics. Soft robotics use soft, elastic deformable structures that provide unique opportunities in uncertain and dynamic task environments like grasping unknown shaped object, non-invasive surgical procedures, prosthesis and haptics. A silicone actuator made using this technology can provide the intended form of mediated touch. With research on the form-factor and other properties, an actuator suitable for physiotherapy application can be realized.

This wearable that mediates touch should be ergonomic and simple for day to day use. To achieve this goal, soft wearable exoskeleton techniques were adapted, rather than the traditional rigid ones. Most of the rigid exoskeletons available in the market support day to day physical work and personal life, acting as an extra muscle [3] or for motion assistance and rehabilitation [4,5] [8]. Soft exoskeletons make use of smart textile technology to provide better interfaces with the human body. It is more light weight, with unconstrained movement and synergistic interaction with the wearer. A smart textile is a fabric that is incorporated with functionality by integrating electronics or imbuing sensing properties. A review by Lina et. al. [9] sheds more insight on the technology and its usage. A fabric can be extrinsically modified by attaching actuating and sensing elements or using coating techniques such as screen printing, electrode-position, thermoset coating and so on. Intrinsic modification of the fabrics can be achieved by intertwining the sensing material into the fabric using methods such as embroidery and silk screening.

As a wear sustain project, the system has to be as sustainable as possible. Even though the chosen material for soft actuators (silicone) is not biodegradable [6], it is not only durable but also more environmentally friendly compared to the plastics [7]. To ensure long term use of the design, a personal relationship has to be formed between the device and the user; what sensoree refers to as ”emotionally durable design”. To reach that goal, user centric research has to be conducted.

[1] http://sensoree.com/
[2] https://wearsustain.eu/
[3] https://eksobionics.com/eksoworks/
[4] https://eksobionics.com/eksohealth/
[5] https://rewalk.com/
[6] https://www.scientificamerican.com/article/earth-talk-silicone-tally/
[7] https://clearandwell.com/why-choose-silicone-instead-of-plastic/

2 Background

2.1 Related Work

Even though there are many devices that aid in the physiotherapy process, there aren't many that utilizes the soft robotics and smart textile technologies. One of such devices is SOPHIA [5] , a prototype developed by McConnell et. al. for physiotherapy. It is a modular rehabilitation system for stroke patients that uses a BMI controlled soft robotic exoskeleton with sensorized gloves for active and passive rehabilitation.

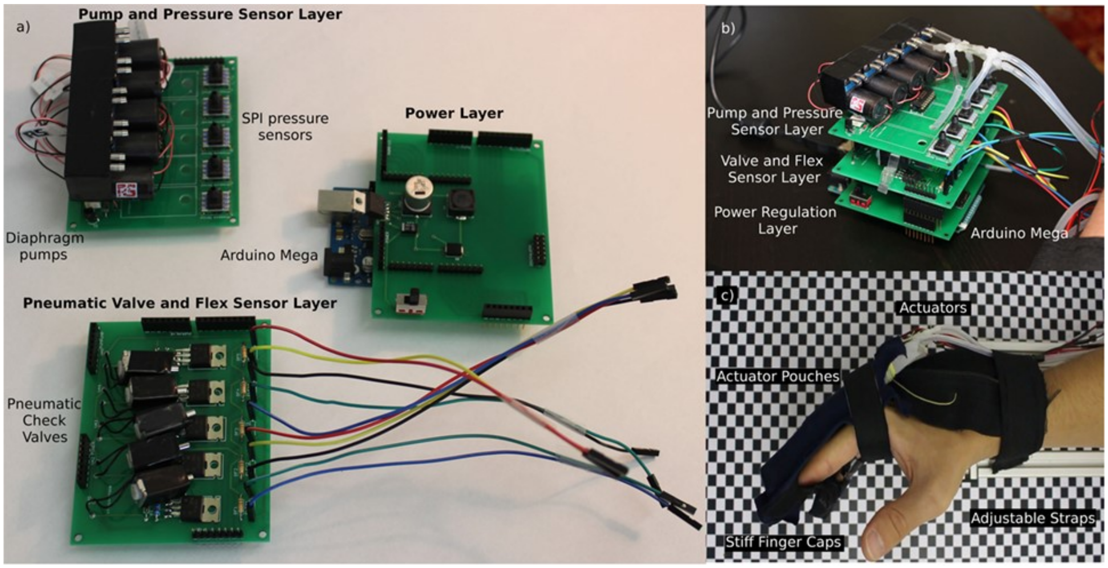


Figure 1: a. Different layers of the electronic system b. Electropneumatic system formed by stacking all the layers c. soft exoskeleton glove [5]

As it can be seen in figure 1c, a soft exoskeleton glove was designed that contains five soft actuators which are controlled by the electropneumatic system shown in figure 1b. To read the motion of the fingers and hand, flex sensors are integrated into the glove. The experimental setup for rehabilitation exercises can be seen in figure 2. The subjects wears a neuroheadset that reads the EEG signals and when an arrow pointing to the right side is seen on the screen, the subjects have to imagine opening their hand and imagine nothing when arrow is pointed to left side. When the subject thinks about opening the hand, control signals are sent to the glove and the soft actuators inflate, aiding the process of opening the hand. And when they think nothing, the actuators go back to normal state. These two steps are repeated multiple times with different combination for around 8 minutes for an efficient training session.

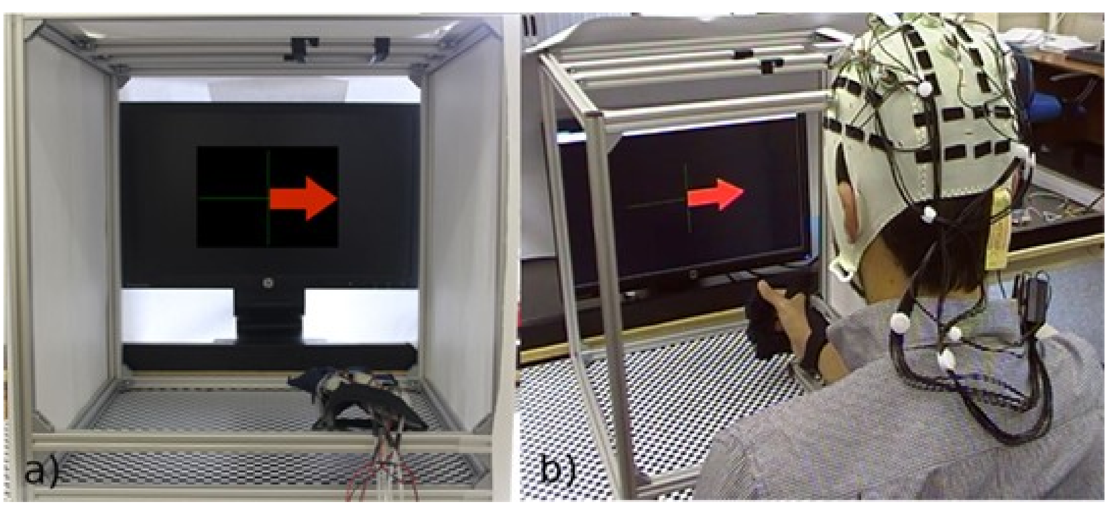


Figure 2: The experimental setup with and without a test subject [5]

Pressure vest is another simple design that utilizes both the above mentioned technologies to create a simple wearable that helps in coping with stress related situations. Using a simple hand pump, the vest can be inflated that provides hug like pressure to calm down and the pump release valve can be used to remove the hand pump after the vest is inflated. Figure 3 shows the vest and the hand pump. Other examples include a novel soft actuator design [6] that can be used in

Figure 3: Pressure vest from Squease wear [21]

various applications that demands enhanced mechanical performance and a full body exoskeleton [7] that can be used for limb retaining, rehabilitation or power assist operations. (For more applications, the reader can refer to Smart Textiles [8], Designing smart garments for rehabilitation by Qi Wang [10] and a paper by Mecnika et. al. [11].

Flexo is the third design in the series of bio-responsive pneumatic wearables that we are focusing in this project. AWE Goosebumps [9] is the first design that displays the feeling of Awe in tangible material. This design focuses on augmenting the feeling of awe that results in the physical manifestation of tingles, chills or goosebumps. The design consists of a layer of silicone inflatables with laser cut kirigami skin over it. Programmable LEDs are integrated onto the wearable that will aid in amplifying the feeling detected. The blueish color on the wearable, as seen on the left side of figure 4 is the ideal state of the wearable and when the Awe is detected, the color on the wearable changes and the silicone inflates as seen on the right side of figure 4. In idle state, the wearable visually displays the breathing pattern of the wearer by pulsating the LED colors from blue to teal. When the Awe is detected, the silicone pockets inflate resulting in an outward elevation of laser cut kirigami skin, imitating the rising skin hair and was visually enhanced by bright pink glow through the wearable.

AWElectric [12] is the second design that adds remote communication to the AWE goosebumps design.The main idea behind the duet design was to transfer the feelings felt by one wearer to another and it has been achieved using a user centric design that involves smart textile, bio-sensing and soft robotics technologies. The design comprises of two wearables, one was integrated with biosensors to read the emotional peak of the Awe while the other receives the sensation via audio tactile fabric. Inspired by single cell networks [12], a structure of five and six sided polygons forming a geodesic architecture was chosen for the skin that would be responsible for mediating the feeling of awe. Based on the qualitative study with 12 feeler interviews, the location and color choices for the final design were chosen. Changes in electro-dermal activity

[8]https://www.tudelft.nl/en/ide/research/research-labs/emerging-materials-lab/smart-textiles/

[9]http://sensoree.com/artifacts/awe-goosebumps/

Figure 4: Ideal state of the wearable (Left) and expressing the Awe on the wearable with inflating silicone pocket (Right) [12]

(EDA), heart rate variability (HRV) and breathing were used to detect the feeling of awe. Figure 5 shows an EDA circuit with integrated optical heart rate sensor that was designed to detect the above-mentioned bio-signals and are transmitted via a Bluetooth module controlled by mini controller board.

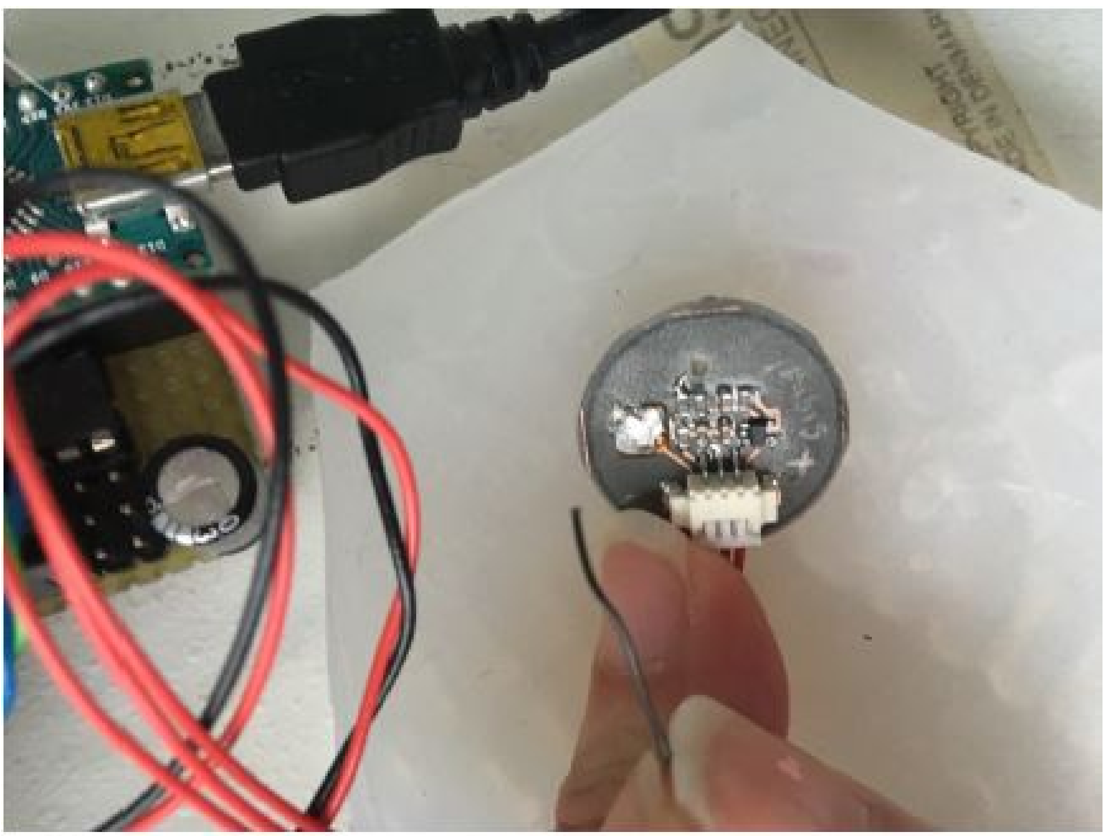
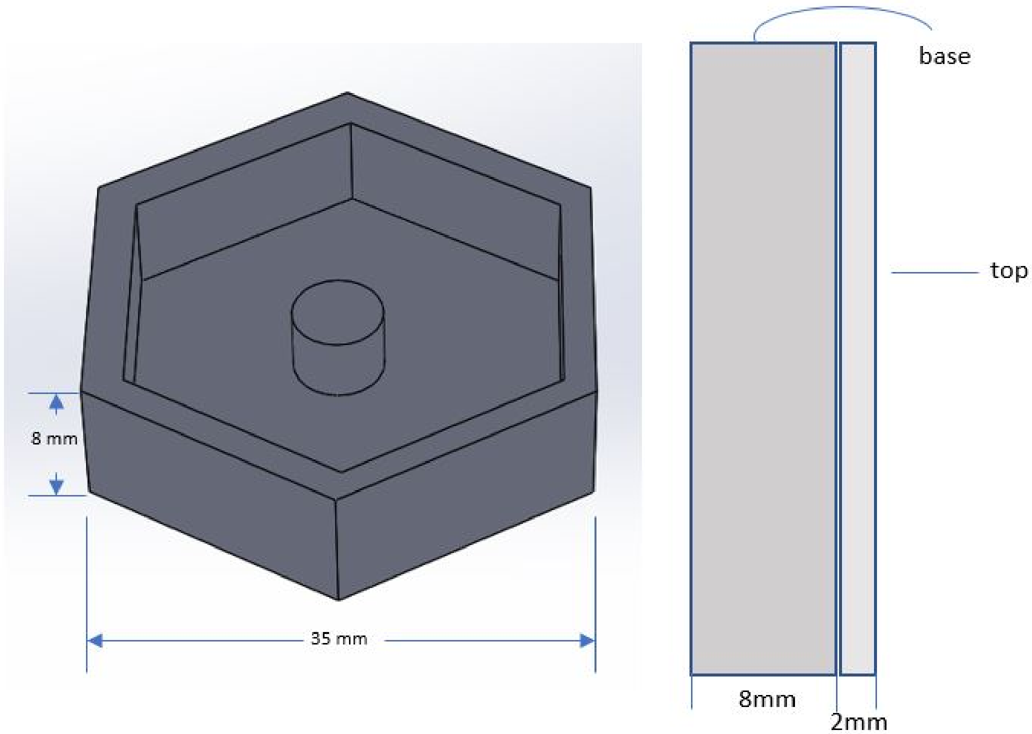


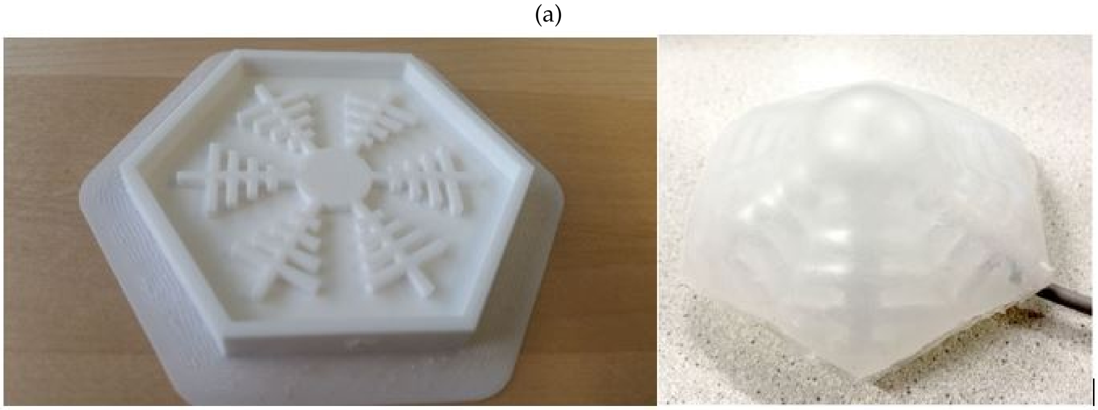
Figure 5: The EDA sensor for the AWE Goosebumps [12]

Silicone inflatables have been used to mimic the shimmer of the exited skin. The inflatable pocket consists of two layers, bottom and top. The top layer is mostly a flat silicone strip to seal the bottom layer which has an inflatable area. Using Soft robotics toolkit [10] as an inspiration, many versions of silicone pockets have been designed using 3D printed molds and an example mold design can be seen in figure 6(a), which can be used for silicone inflatable casting. Using silicone Ecoflex 00-30 [11] which has most skin-like characteristics, a hexagonal shaped pocket with internal snow flake pattern was realized which can be seen in figure 6(b). A small controller board using aurdino micro-controllers with an amplifier circuit connected to

[10]https://softroboticstoolkit.com/
[11]https://www.smooth-on.com/products/ecoflex-00-30/



(a)



(b)

Figure 6: (a) 3D view of the bottom mold (left) and the two layers of pocket (right). (b) 3D printed mold (left) and its silicone casted pocket (right) [12]

pumps and valves was used to control the air flow in the pockets. The circuit also include a Bluetooth module for wireless communication between the two wearables. To tickle the skin and simulate the feeling of frisson, a speaker is embedded into the fabric. Figure 7 shows the back-side module of the final design in which, the audio tactile is in between two 3D printed goosebumps fractals. These fractals mimic the body's articulations, movements and expressions. The inflatable silicone pockets placed under this fractal inflate when an emotional peak is reached, inflating the hexagonal peaks on the fractals creating a vibration at the center from the embroidered speakers. This vibrating frequency is imitated on the receiver's wearable providing an awe sensation.

2.2 Previous Work

Using the AWE project discussed in the previous section as a reference, a new design model has been realized which visualizes the emotions detected by the bio-sensor using soft actuating pockets. The hexagonal design of the silicone actuator has been retained and an array of these actuators is stacked over a wearable jacket. The silicone actuator array is positioned on the back of the wearer with visual breathing pattern imitated by a strip of programmable LEDs. The actuation of the pockets was controlled by the control board similar to the one used in AWElectric, close looped with biosensor feedback. When an Awe has been detected, the silicone pocket inflated outwards and this phenomenon was also visually represented

Figure 7: Final design of AWElectric [12]

with simultaneous change in the color. Figure 8 shows the final wearable design that uses an array of ten silicone actuators and the control board was placed below the array camouflaged using a 3D printed design.

Based on the bio-sensing design used in the previous project, a new one measuring heart rate (ECG), respiratory rate (stretch sensor), skin resistance (GSR) and motion has been realised. An additional input device [14] was also developed by which the patient can confirm his/her emotional state providing a closed loop feedback between the client and the therapist. Escalade(bio-sensing setup)[13] and the feedback device can be seen in figure 9

Being a user centric design, studies were conducted in both autism spectrum as well as in physical therapy sessions. A toolkit consisting of a single pocket inflated using a syringe was tested on physical therapy clients to understand the impact of this mediated touch model. A collaboration has been formed with the German Research centre for Artificial Intelligence[12](DFKI) to help with biofeedback data sampling and processing. Using an existing data logging app, GSR data was used to perform sampling and the results were compared with the DFKI's app and the results were reported positive by clients and therapists. And to comply with the data privacy laws, a consent form has been designed with the help of the Ethics committee at University of Twente.

[12]https://www.dfki.de/web/

Figure 8: The wearable design prototype of the first iteration

Figure 9: Escalade setup (top) and emotion input device (bottom)

3 ANALYSIS

3.1 Design Research

Design research is the process of presenting ideas and the receive user feedback that will be used in rapid prototyping of the design elements. It will provide more insight in the reality versus what was expected from the design outcome. This research focuses mainly on the end users to make the design more user centered, creating highly usable and acceptable design elements. Iterative design is a form of design research where the processes of design, prototype and analysis are repeated in cycle until desired product is achieved. Flexo, being a project that involves interaction and expects a design that can form a personal relationship with users, design research methods are used in the project to achieve the desired goals. The choice of approach was also influenced by the Interactive inflatables studio project by Kristin et. al.[15]. The topics covered in the studio align with the elements involved in this project, making it more suitable than other approaches.

3.2 Silicone actuator

3.2.1 Design of silicone actuator

Silicone pockets are soft inflatable actuators can can be used to apply forces on the surface of the skin, creating a physio therapeutic effect. The silicone pocket that was used in the previous work has dimensions of 70x80x15 mm with hexagonal shape. Due to its large surface contact, the force applied on the skin is spread over an area. Acupressure[16] is one of the physio therapies that uses point pressures and as a project requirement, this will be used as a reference for the design. Thus, a new pocket design is needed that can provide point forces. The behaviour of the pockets differs based on the shape and side of the air chamber that inflates, which also influences the forces produced. To study this behaviour, pockets (35x40x6 mm) with different internal shapes were produced. Figure 10 shows behavior of a few pockets inflating over a given time. It can be noticed that some pockets are inflated towards both base and top layer directions.

3.2.2 Forces produced by the silicone actuator

When the pocket is inflated, it lifts itself with almost negligible forces applied towards the surface it is placed on. To achieve forces, restraint is required as shown in the left side of figure 11. In the setup, the pocket is fixed on a stiff surface, leaving the top layer open. When the pocket is inflated, forces are produced on either side of the pocket. If the resistive force of the stiff surface (F_r) is greater than the force applied by the bottom layer of the silicone layer (F_b), certain force (F_t) can be achieved that can apply pressure over a surface.

To study the forces produced by these pockets, a test setup was built as seen in figure 12. A Force Sensing Resistor (FSR) is used to measure the amount of forces produced by the pocket in both directions. The bottom of the pocket is fixed to a table surface which has very high resistive force compared to the palm of the person on the top of the pocket, which is placed casually with no additional force applied. Table 2 in the appendix lists the forces that have been measured on both sides and it can be noticed that the forces applied on the skin are less compared to the one towards a stiff surface. This is because the skin surface deforms when the silicone pocket tries to inflate, requiring less force. As it can be seen in figure 13, the pocket raises up a little as the bottom layer can't deform the table surface and it also resulted in higher inflation towards the skin due to its low resistivity. It should be also noted that top layer inflating distance and it's applied force is affected by factors such as the position on the body where the pocket will be placed, thickness of the skin layer and the type of restraint (table surface in this experiment).

3.2.3 Lifetime of the silicone pocket

After the silicone pocket providing point forces has been realized, the next question to answer is on how long this silicone pocket design can sustain. It would be a waste if the pocket is useless after couple of inflations, so the test setup shown in figure 12 is used to study it's longevity. The pocket was inflated for 1000 cycles with 2 seconds of inflation time and the forces are measured using the FSR placed between the bottom layer and the table surface. The FSR on the top side of the silicone pocket was not used in this experiment and the palm is placed on the top of the silicone pocket only at the iterations of 40, 400, 650, 800 and 950. It can be clearly noticed from the graph shown in figure 14, that the forces produced by the silicone pocket are decreasing. The red dots represent the forces recorded when the palm is placed; even though there is increase in forces due to resistance on both sides of the pocket, it is recorded low at last iterations. Since the silicone pocket can't last longer, alternative ways have to be explored.

3.3 Exo-skeleton

Twelve pressure points that are used for well-being were chosen by the client as shown in figure 15 a. The horizontal dotted line represents the shoulder of a person and the vertical line being the spinal cord. The twelve small blue atom structures represent approximate locations of the pressure points; six pressure points on the back, two near the neck and four near the chest. Silicone actuators have to be placed on these given pressure points to provide required forces on the skin. Thus, a skeletal frame is required that not only holds all the relevant components but also act as a restraining frame for the silicone pockets.

The first design was inspired from the general headband design and it uses two headband like structures that can hold the skeletal design that is hung over the shoulders of the person. Figure 15 b shows the prototype that covers the pressure

Figure 10: silicone pockets with different internal shapes in inflated state

points on the left side of the spinal cord.The headband structure that clips to the shoulder is extended through modular spring structures that hold the pockets against the body. The ends of these structures will be attached with radial plastic disks that restricts the silicone pocket inflation, providing forces towards the skin, when inflated. The main drawback of this design was the durability of the structure for day to day use; the user should be very careful not to break or miss-align the skeletal structure. To address this issue, designs that involve less mechanical structures were explored. Form factor of body fit jacket was chosen that can hold all the components and with right choice of textile material, stiff outer layer that can restrict the outward inflation can be achieved.

3.4 Control system

To control the pockets that cover the 12 pressure points discussed in the previous section, a control system is needed that can control multiple pockets. In the previous work, a system was designed that controls a single pocket for a desired force or pressure, which can be seen in figure 16. It uses a closed loop structure either with feedback from force or pressure. When a certain force or pressure have been achieved, the control system either maintains that pressure or automatically cuts off the air flow, depending on the application scenario.

Using it as a reference, a simple control system has been realized that can control multiple pockets. Figure 17 shows the setup and its schematic diagram, built to control five to ten silicone pockets. As it can be seen, the breadboard is controlling five pneumatic valves using Arduino. The Darlington transistor array was the first choice but due to its high voltage drop, a small circuit using 2N3905 transistors was used to operate the pneumatic valves; while the array was used to operate the air pumps which have lower less voltage requirements. From the tests, it was noticed that each valve can control no more than

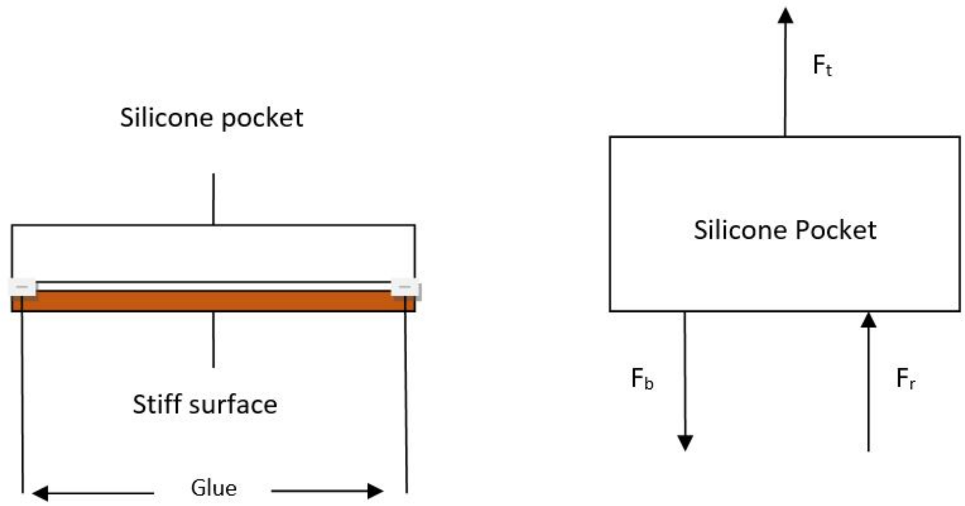


Figure 11: Basic pocket setup to achieve forces (left) and the free body diagram of the setup (right)

Figure 12: Test setup to measure forces produced by different silicone pockets

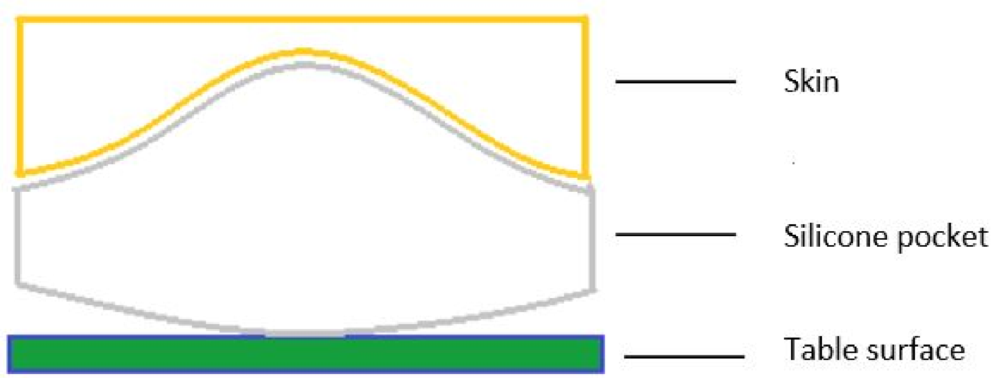


Figure 13: Side view of the test setup when the silicone pocket

two silicone pockets efficiently. Adding more pockets per valve decreases the air flow in each of them, reducing the inflation of the pockets. Assigning individual pump and valve for each pocket will provide faster inflation; but would increase the

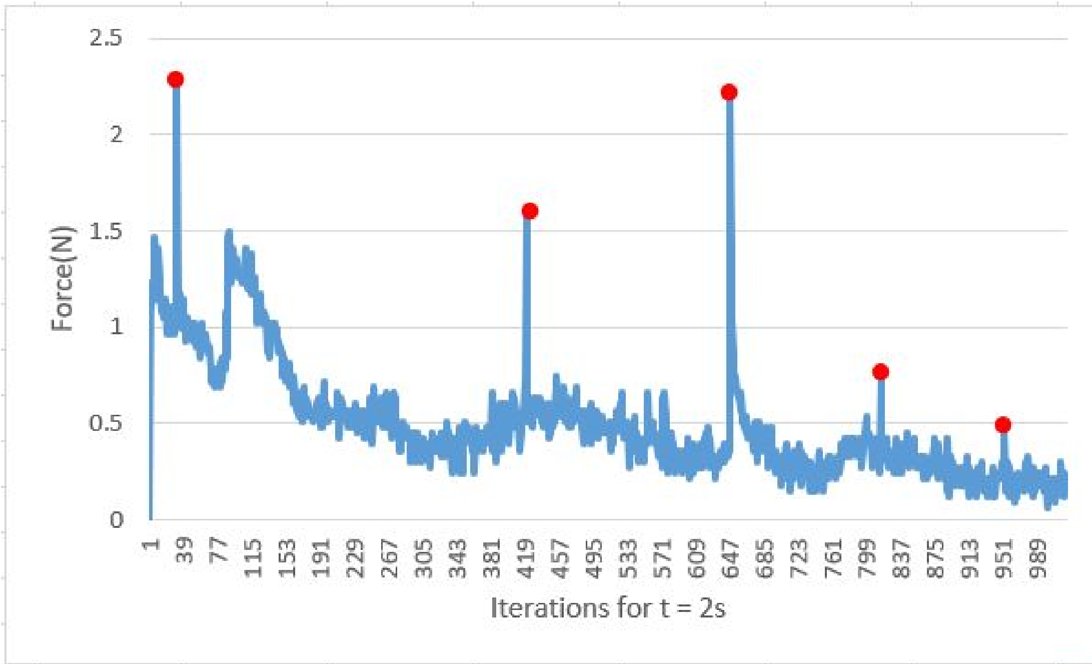


Figure 14: Graph showing the varying forces for 1000 iterations

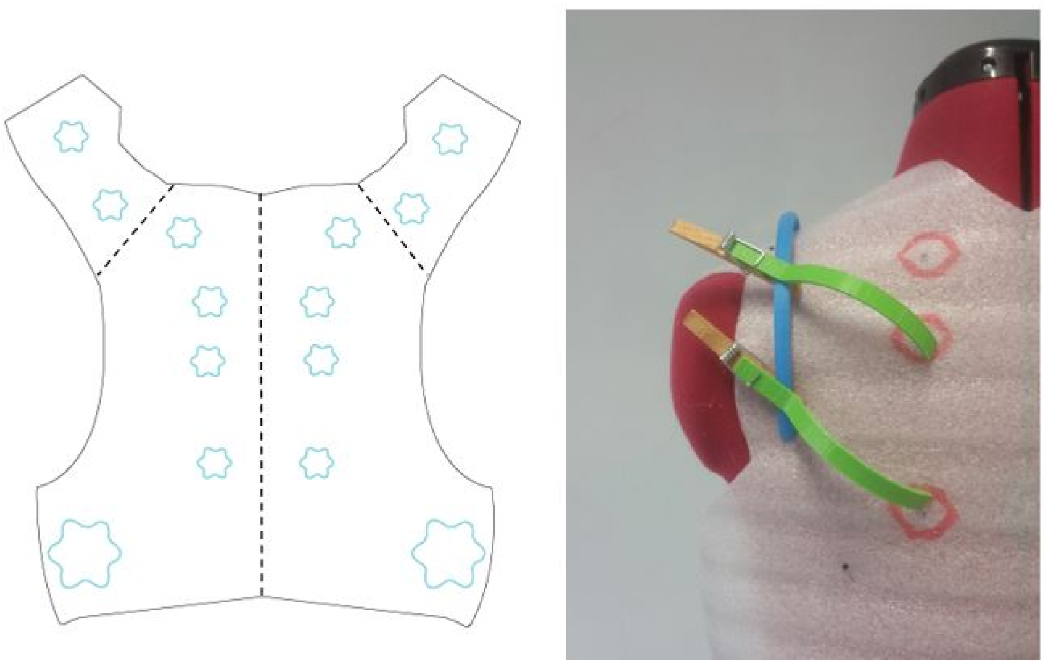


Figure 15: a. Final pocket locations b. Exoskeletal design to support pockets

amount of electronics used. Thus it is concluded that using one valve and a pump for every two silicone pockets is the optimal solution.

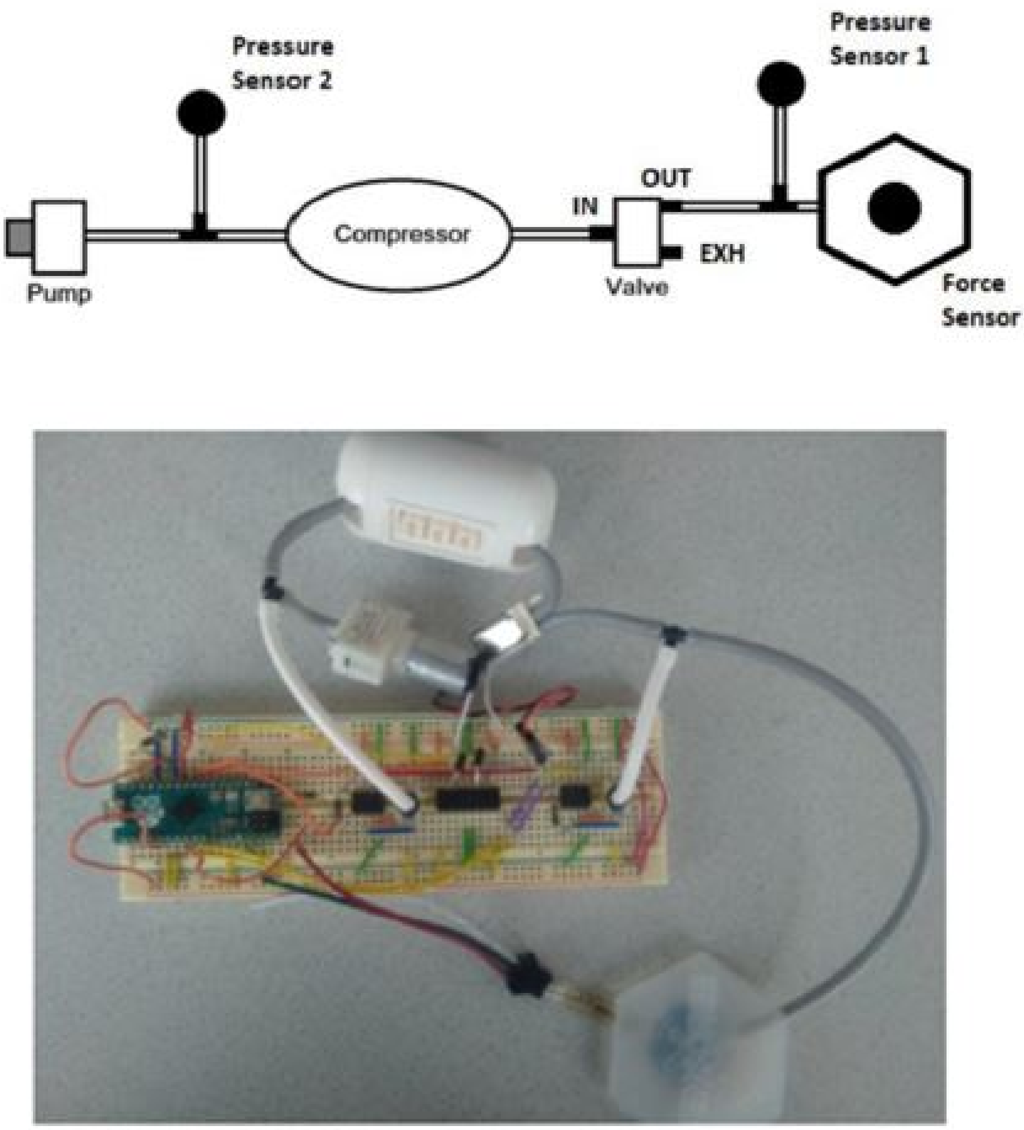


Figure 16: Initial control system design overview and its prototype[17]

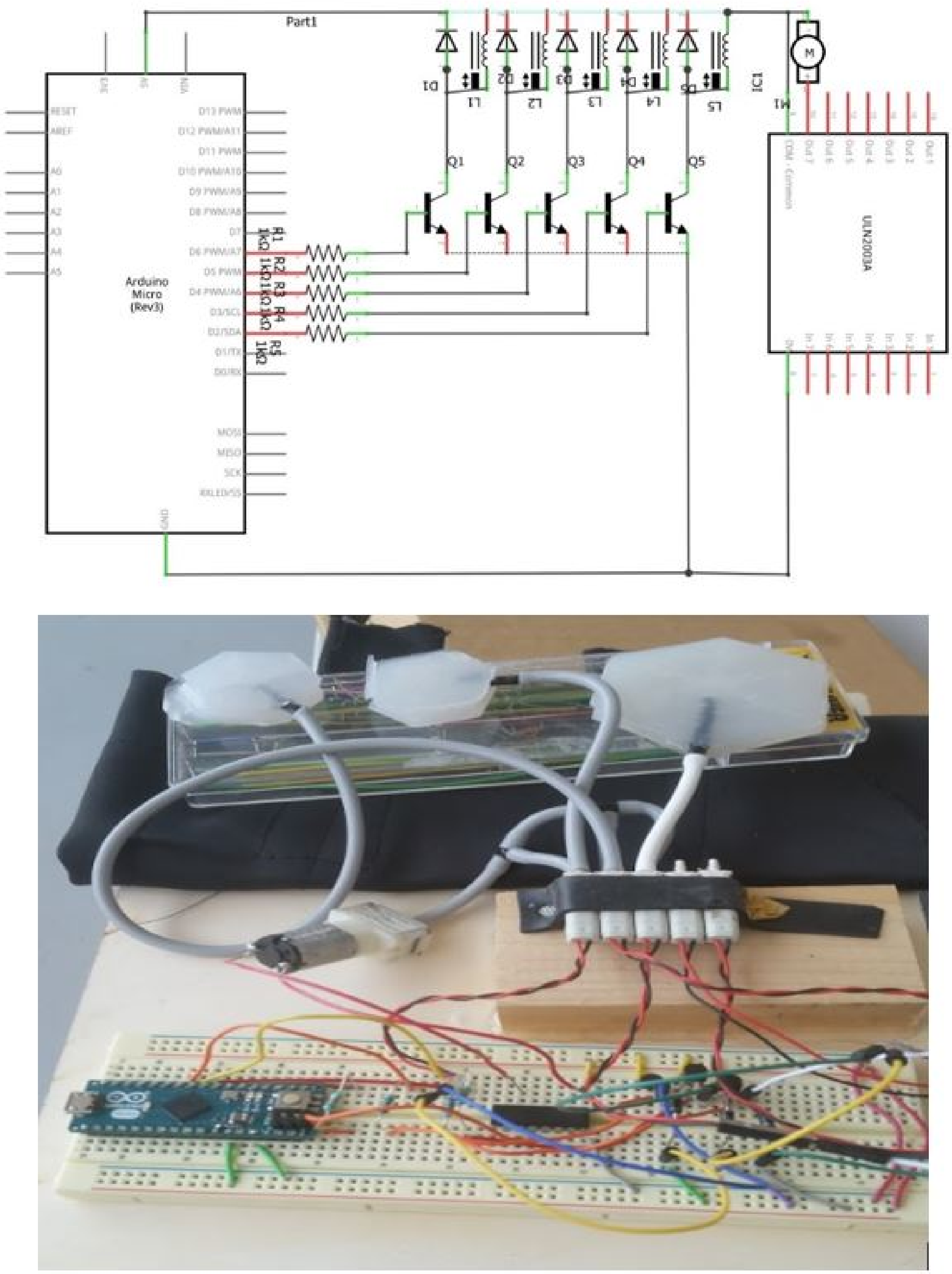


Figure 17: The schematic diagram of the control system(left) and the test setup(right)

4 DESIGN

4.1 First Iteration

Imitating the sense of touch is one of the main requirements of the project. Even though the silicone pocket design achieved in section 3.2 can imitate touch, user studies would provide more insight on the integration of the pockets onto the wearable. Thus, a prototype is needed that can be used for user studies. A silicone strip with nine pockets (left side of figure 18) was casted from a 3D printed mold and these pockets are pneumatically controlled using the control system discussed in section 3.4. The control system is pre-programmed to perform a series of different inflation patterns, starting with all pockets inflating together and then continued with random inflation individually as well as in sets. The whole inflation pattern will run for two iterations, one with high forces and other with low forces. Figure 18 shows the final test prototype that was realized in the form of a wearable band.


Figure 18: The silicone strip with nine pockets(left) and the prototype using it(right)

User studies were conducted as part of the project, using the prototype to answer three main questions that would help in making final design choices.These questions were formulated based on the intention of the client to use the design in physiotherapy. Each physiotherapy session have a certain time-period and physical touch on certain area of body is involved. On design perspective, exploring these questions will aid in designing a better wearable that is more ergonomic and flexible in design process.

- How can the design be worn comfortably for longer duration
- Is direct contact of silicone pockets to the skin an influential factor both emotionally and physically
- Does the usage of the design over different sensitivity areas influence the above two factors

The target group involve people of different age and gender and it took maximum of ten minutes per person. The inflation pattern discussed previously will be run with and without a fabric in between the skin and the silicone strip. As seen in figure 19, it was used in the areas of palm and wrist which has different skin sensitivity.

Feedback has been recorded on different aspects such as the feel of touch, comfort, sensitivity of varied force etc. Even though the sensitivity on the palm was higher, the participants preferred the wrist as in their terms, “it’s a new feeling experience on wrist compared to the ticklish feeling on the palm” and they can clearly distinguish the different forces. Another notable feedback was on the clear feeling of the point forces and where exactly on the skin they are acting upon. Many participants can clearly feel and locate the points where the force have been applied when the silicone strip was directly in contact with the skin but the cold touch over the whole area that has been in contact with the skin was not very comfortable. In the end, all the participants were really happy and were open to daily usage of the design as part of the lifestyle.

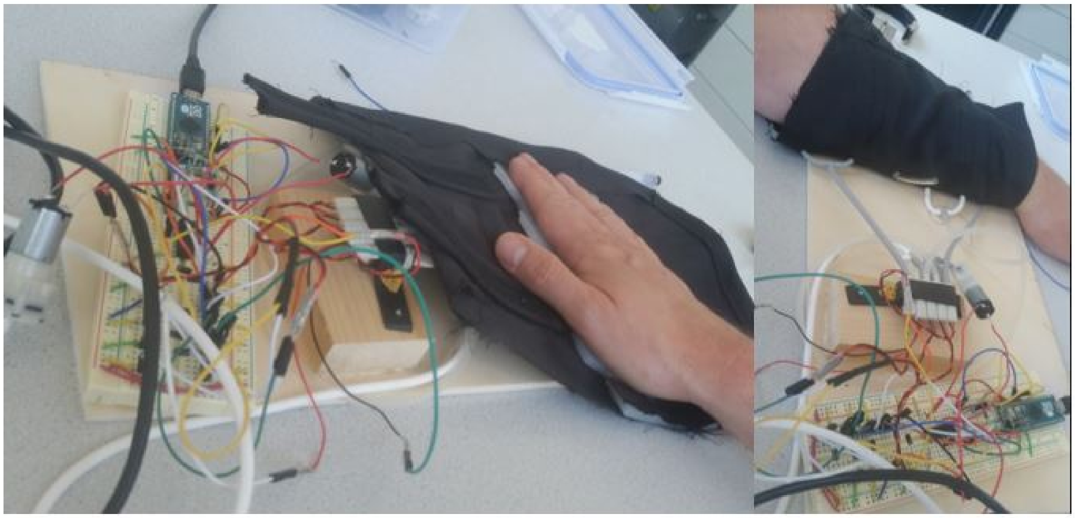


Figure 19: Test scenarios used for user study

Based on the feedback from the user studies, changes have been made to the prototype as seen in figure 20. To keep the effect of silicone touching the skin directly and comfortable enough to wear for a longer period, a flexible fabric layer was used above the silicone strip but with slots at the points where inflatable pockets are available. When no forces are applied, it lays comfortably on the skin like any other hand band; when inflated, the silicone pocket pops out of the laser cut slots on the fabric inflicting a direct contact force on the skin. the design that will be used as reference for the last iteration as well as a prototype for user experience in events has been realized and it can be seen in . This design will be used as reference for the last iteration and can be used as a prototype to provide user experience in exhibitions and user studies.

Figure 20: The final design using the feedback from user studies

4.2 Second Iteration

Based on the requirements of the client, a design overview of the project focused on tele-operated physiotherapy is envisioned and can be seen in figure 21. Both the physiotherapist and the client wear the exoskeleton so that the amount of force applied on the client's body can be felt by the therapist too. The forces are applied using a haptic device connected to the system on the therapist side and will be communicated through a server to the client's computer which is connected to the exoskeleton and in-turn the biosensor (discussed in section 2.2) provides live data on the client's condition to the therapist's computer. In this section, the following areas of the project will be discussed, that were realized and tested to an extent.

- Exo-skeleton
- Haptic interface
- Communication
- Graphic User Interface (GUI)

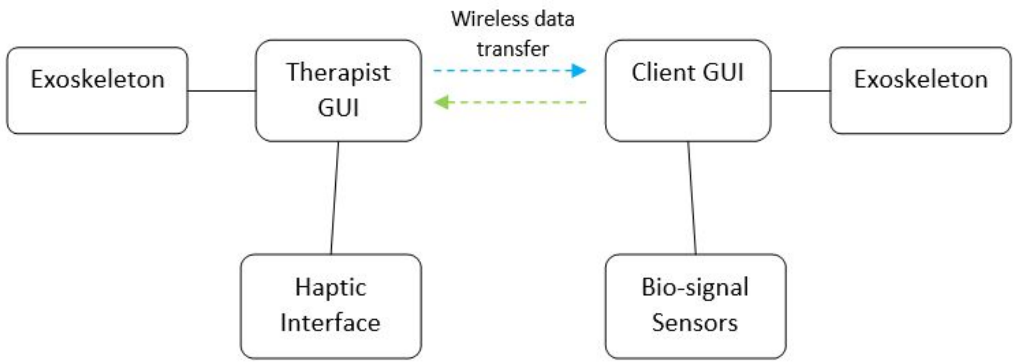


Figure 21: An overview of the final design

4.2.1 Exoskeleton

An exoskeleton have to be designed to hold all the components of the design and as discussed in the section 3.3, a sleeveless jacket form has been chosen over the headband model and it contains multiple layers of textile as shown in figure 22. The innermost layer that touches the skin has slots that are laser cut at the points where the pockets will be placed to imitate the feeling of touch. The silicone pockets and the LEDs are added to the second layer and the outer layers use different fabric materials that would provide enough stiffness to act as the restricting frame for the embedded silicone pockets.

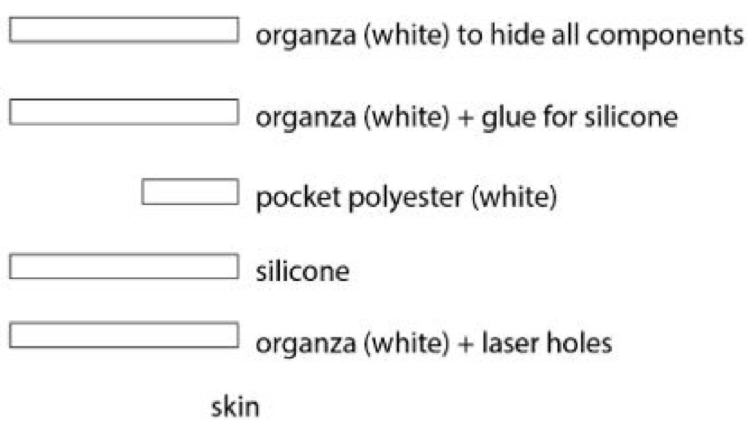


Figure 22: General representation of different layers of the wearable

Individual silicone pockets cannot be directly integrated onto the fabric due to its low support structure around the inflating area that is needed to hold the pocket tight on the fabric. Thus a silicone pocket framework is needed that can be integrated onto the second fabric layer. The initial design (figure 23a) uses a very basic two mold approach covering all the pressure points at intended locations but with twelve pockets, the alignment of air tubes connecting the pockets to the electronics was not ideal and the pocket design itself gave a hard time to connect them with air tubes. The second design (figure 23b) addressed the previous design challenges and was also more stable on the textile due to its one-piece model unlike the later design. But, one major problem faced while casting was the complexity of sealing the two layers of the design; there was a high chance of blockage in airflow channels making it completely unusable. Another drawback was that if one pocket is damaged, the whole design must be replaced. This led to the final design (figure 23c) that uses pairs of pockets on either side of the spinal cord rather than individual pockets for inflation. It reduces the number of air tubes to half and the pocket design has a small notch that makes the tube connection very easy. The design also produces a bending effect that pushes the pockets towards the skin.

Figure 23: a.Two piece model b.One piece model c. Two pocket model

With the final design choice of silicone layer, now the next requirement is the control system to actuate these pockets. The general schematics used for controlling the exoskeleton is similar to the one discussed in section 3.4, but on a higher scale. Figure 24 shows the control board (top) that can control eight pneumatic valves, five air pumps and an LED strip for visual effects. External power supply was used to operate the pumps and valves while the LEDs draw power from the arduino itself. As seen in the 24 (bottom), a setup was realised that connects the control system to a sample silicone pocket layer. Test runs were conducted by inflating different inflation patterns along with LEDs that visualize the breathing pattern of the person and the location when a certain pocket is used. The breathing pattern uses blue-green variance and the interruption is bluish white.

While a life size dress form was used as a reference for the measurements of the wearable jacket, the innermost layer can be seen in the figure 25a that contains laser cut orfices at the desired locations discussed in section 3.3. Figure 25b shows the layer above the laser cut fabric which was integrated with the final inflatable pocket framework and the LED strip that was used for the visualization. The individual LEDs are placed carefully in the positions near to the pockets to avoid the influence on inflation. All the electronics related to control system are placed on a fabric strip and has been placed at the bottom of the jacket inside a pouch like structure, as seen in figure 25c. Magnetic strip was used to open or close the pouch, so that components can be replaced with ease whenever needed.

4.2.2 Haptic Interface

Until now the pockets were inflated randomly using pre-programmed sequences. As part of the project requirement, the therapist should have the control over the individual pockets on the wearable.To achieve this, an input device is needed and Roli's Seaboard Block [13] that is pressure responsive with 5D touch technology is used as a haptic input device for this project. An algorithm is written for the processing software [14] and when a key is pressed on the keyboard, the input value is read by this software and is sent to the aurdino chip on the control board. Two variables are read from the input device, one that defines the location of the key pressed on the haptic device and the other, records the tap velocity with which the key was pressed. While the location of the haptic keys are used to connect different pockets, which will be discussed later; the tap velocity is used to define the amount of forces the pockets can produce.

Using an algorithm written for arduino, the keys on the haptic input device are assigned to the different pockets on the exoskeleton to perform intended location specific pocket inflation. Figure 26 shows the one to one mapping between the haptic device and the soft actuators on the exoskeleton. The additional keys in the haptic device can be used to pre-program different actuation patterns similar to the one used in the first iteration, providing additional functionality.

[13] https://roli.com/products/seaboard/
[14] https://processing.org/

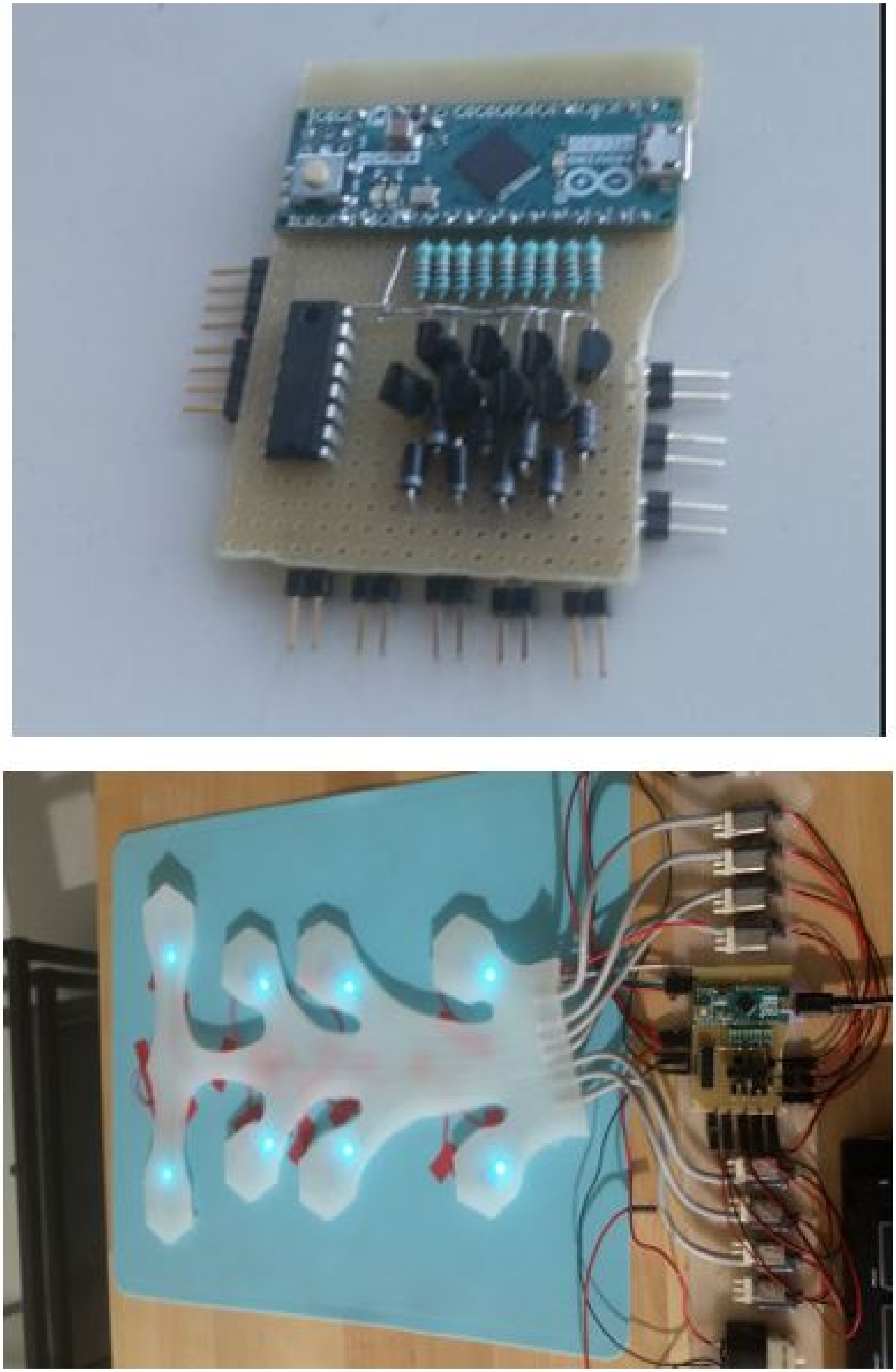


Figure 24: The control board(top) and the test setup(bottom)

4.2.3 Communication

Proper communication channel has to be established for efficient control of the silicone actuators. Figure 27 clearly shows how different entities of the system communicate to achieve the desired output. It can be clearly noticed that there are two

Figure 25: a.laser cut fabric b. silicone actuator pockets and LEDs on a fabric c. pocket holder for control system

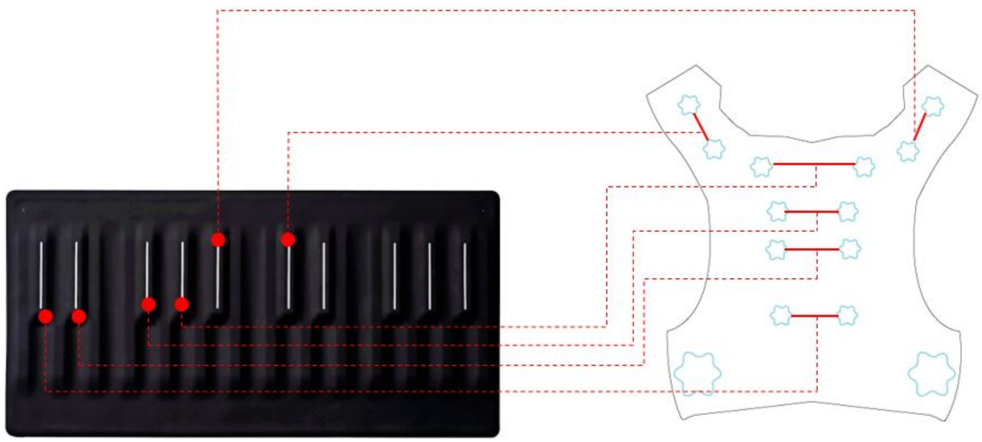


Figure 26: The mapping of the haptic keys to the pockets on the wearable

sections that communicate serially; haptic side and wearable side. On the haptic side, the processing software algorithm reads the input variables from the haptic interface and it is serially communicated to arduino board on the control system. It also sends the same data to the graphic user interface for visualization, which will be broadly discussed in the next section. The haptic keyboard can use the same haptic keys to transmit different position values for different communication channels. In this design, channel 1 is used to transmit the position and velocity data.

The control system on the exo-skeleton is connected to the computer and the data from processing is sent to the arduino board. Arduino connects the key position to its respective silicone pocket as discussed in section 4.2.2. The velocity input is used to to define the amount of time the pocket inflates, which influences the force applied on the body. Based on the mode of the device, either it sends the data formerly mentioned or the pre-recorded data to the exo-skeleton. Along with this, a parallel process is run that controls the LEDs that were integrated onto the exo-skeleton.

4.2.4 Graphic User Interface

Since the main goal of the Flexo is to provide physiotherapy remotely, visual representation of multiple data is needed for better control on the therapy session with the client. Using processing software, two GUI variants have been realized for physiotherapist and client respectively as shown in figure 28. While the orb displays change in mood of the client and the mood chart defines colors to different emotions, the client can confirm the emotions felt using the mood logger on the interface similar to the input device used in the previous work. This will help the therapist to counteract irregular mood patterns from biosensor and patients input. The video and text options facilitate better communication between the therapist. The data from the biosensor can be viewed real-time by both users in the form of graphs.

While most of the elements described above are only representative on how it would look and work when they are realized, the Flexo activation scheme is the only element that has been realized and tested. It is placed on the left bottom

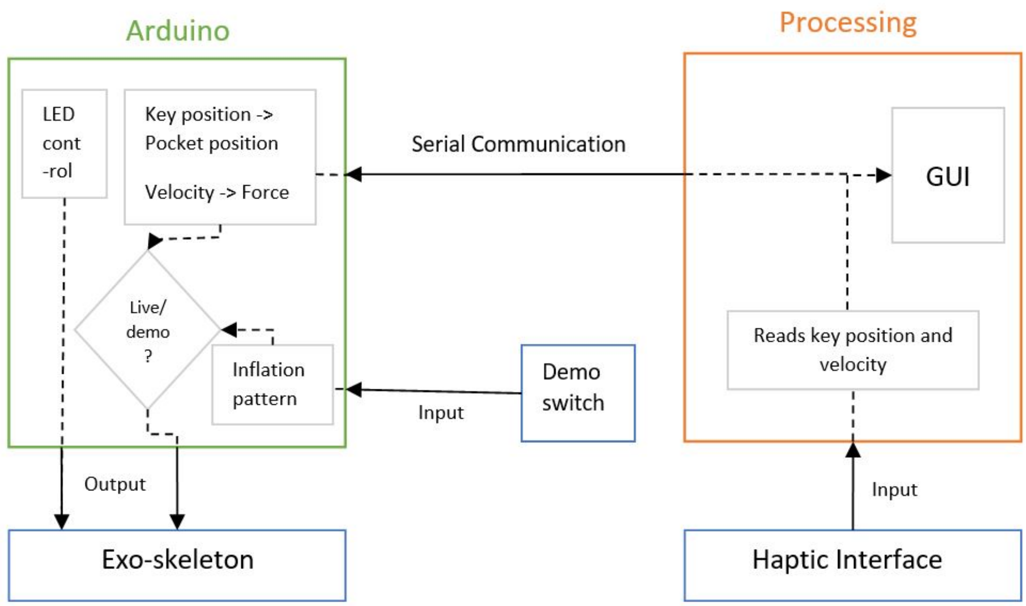


Figure 27: Block diagram describing the communication flow of the whole design

corner of the therapist's GUI with a shape of the jacket with points that represent the pressure points on the wearable. The input data from the haptic interface is used to locate the pressure point that has been used, with reference from the mapping discussed in section 4.2.2. The amount of force applied on the that particular pressure point was also visualized with different shades and sizes of the circle over that location.

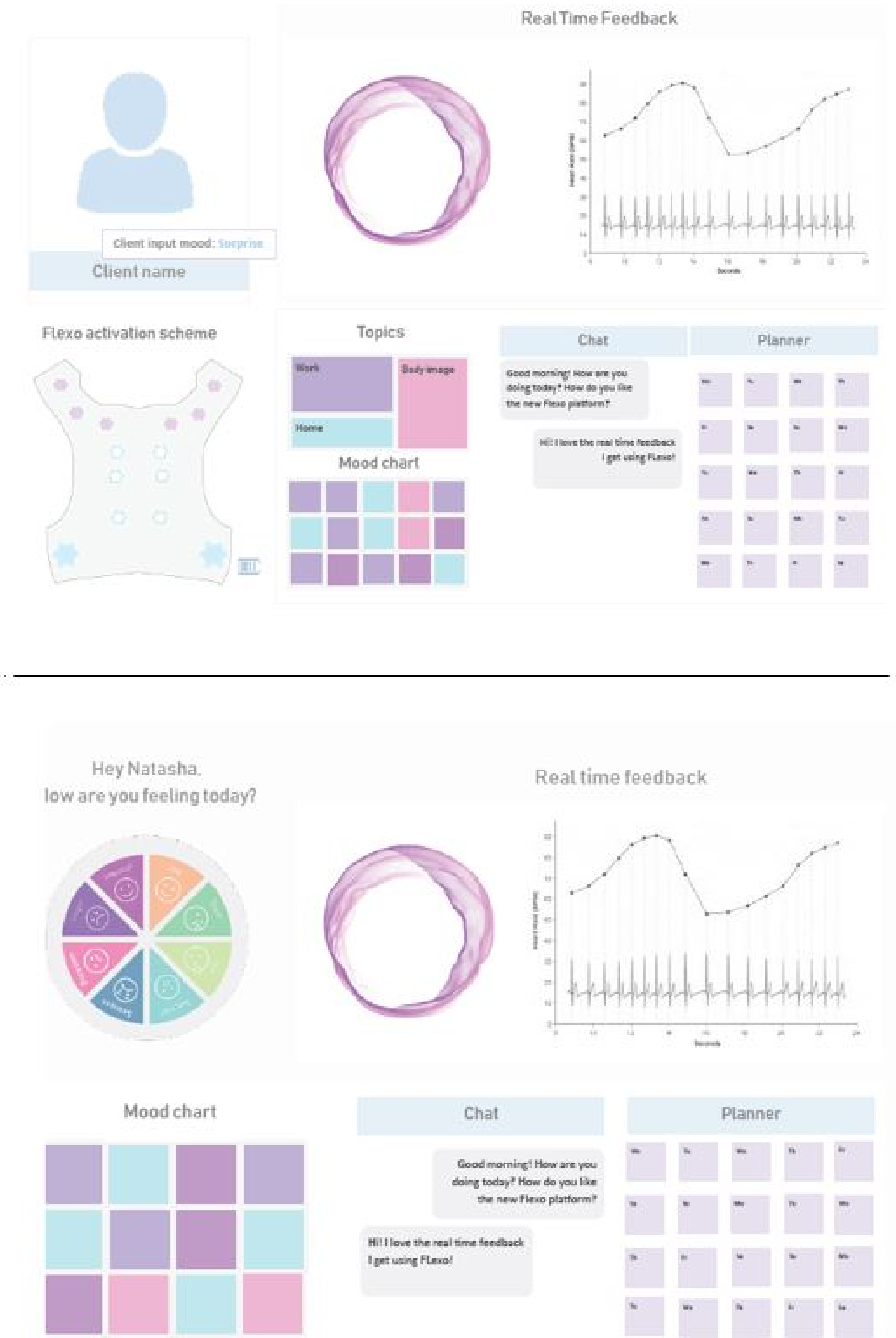


Figure 28: The GUI of the therapist(top) and the client(bottom)

5 RESULTS

5.1 User Feedback: First iteration

In section 4.1, a test prototype has been realized and user test cases were run that influenced the final design aspects. Table 1 lists comments provided by five of the participants involved in the user case study. It took maximum of 10 minutes per session and the names of the participants were kept anonymous to comply with user privacy. This feedback was used to make changes in the design and the resultant design after the changes have been applied can be seen in figure 20 at the end of the same section.

User	feedback
Person 1	"the locations of the pockets can be felt really strong" "It felt like something hard, right amount of force was pushing towards the skin and the touch was nice like massage" "I prefer a fabric layer between the skin and the silicone"
Person 2	"The forces applied on the skin felt like ticklish and more natural on the wrist area" "The touch was very smooth and the direct touch from silicone is preferred" "the feeling of touch on wrist area is a new experience as it is not common"
Person 3	"It was easy to locate the pressure points on palm area" "Textile layer is nice and comfortable for longer use"
Person 4	"The locations of the pressure points can be easily felt but was hard to differentiate change in forces" "With fabric layer, it felt that the applied forces are reduced" "comfortable with textile but easy to feel and locate pressure points with direct silicone contact"
Person 5	"Low forces felt really good" "with fabric layer, it was hard to locate the pressure points"

Table 1: User Feedback from the test prototype

5.2 Final Design

The final design setup can be seen in the figure 29. The setup involves a computer system that provides therapist with the user interface and also acts as the communication medium between the haptic interface and the exoskeleton on the dummy, which will be worn by the therapist. When the therapist presses a key on the haptic interface, the silicone pocket at a certain location will be inflated, exerting certain force on the skin. The whole operation of design can be clearly understood from the process flow diagram shown in figure 30. As discussed in section 4.2.2. the haptic keys are touch sensitive, providing different velocity values on how hard the key is pressed. These values can be used to define the inflation time of the pockets, which in-turn influences the forces generated. In the final design, the velocity range of 0 to 127 was divided into lower and higher ranges providing low (1.6 N) and High (2.4 N) forces for the therapist to use in a therapy session. Multiple readings were recorded for different velocity values. To observe the inconsistency of force measured, multiple measurements were recorded for different velocities in the given range. As see in the figure 31, there is certain error rate for forces measured in every velocity. In this test, the inflation time of the pocket is velocity range increased by a factor of 50; which should increase the forces linearly in an ideal case, as represented by the trend line. But it can be clearly noticed that the forces are non-linear with more stagnant values at higher velocities.

5.3 Exhibitions

Being an user focused design, exhibitions play a vital role in gathering feedback on the usability and acceptance of the design in people's daily life. It is also a stage that provides opportunity for the experts in relevant fields to comment, inspire and collaborate on this new idea.

5.3.0.1 **Design <> Research Exhibition,London (21-23 September 2018)**: As part of the London design festival, the Royal College of Art (RCA) introduced two new research centres, Burberry Material Futures Research Group and the Intelligent Mobility Design Centre. Flexo was invited to exhibit its flexible exoskeleton design where the first and second iteration designs were presented. One of the pictures taken at the exhibition can be seen in figure 32 where Kristin Neidlinger was providing information on the project.

5.3.0.2 **WearSustain Final Event, Brussels (18 November 2018)**: All the 46 teams that were funded by Wear Sustain have to showcase their final prototypes; and Flexo being one of them, Edwin Dertien showcased the final design at the event. The presentation for the event has been made in a way that mimics the remote therapist and client interaction. A snapshot of the video that was presented at the event can be seen in figure 33. A live therapy session was imitated with the video as a tele-call and the haptic inputs in the video reflecting on the exoskeleton worn by the presenter at the event with pocket actuation using the demo function.

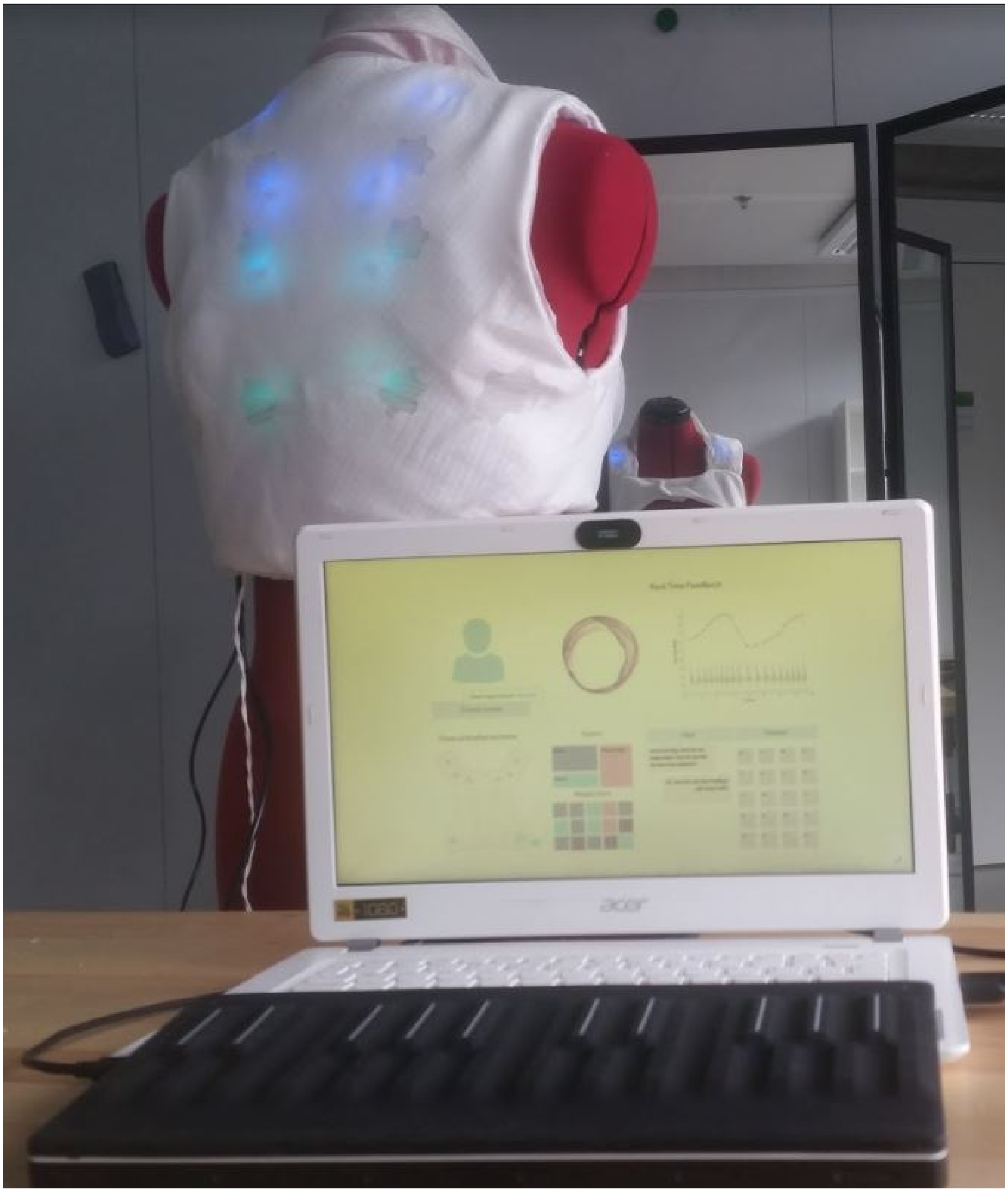


Figure 29: Final design setup using a dummy

5.3.0.3 **ICT 2018 Conference, Vienna (4-6 December 2018**: Flexo was one of the four main projects that were invited to present at ICT with STARTS (Science, Technology and the Arts), an initiative of the European Commission launched under the Horizon 2020 research and innovation programme. Along with a lot of inquiries on the availability and price range, a very positive feedback has been received from the visitors and a couple of them include "This would be great when getting a massage because they always go too deep and I have a hard time telling them my preference." and "This is not fashion tech, this is healthcare.". Invitations for future collaboration with companies like Waag society[15] and Careables[16] were others takeaways from the event. Figure 34 shows the display of the flexo final design at the conference's exhibition area.

[15]https://waag.org/en/labs/creative-care-lab
[16]https://www.careables.org/

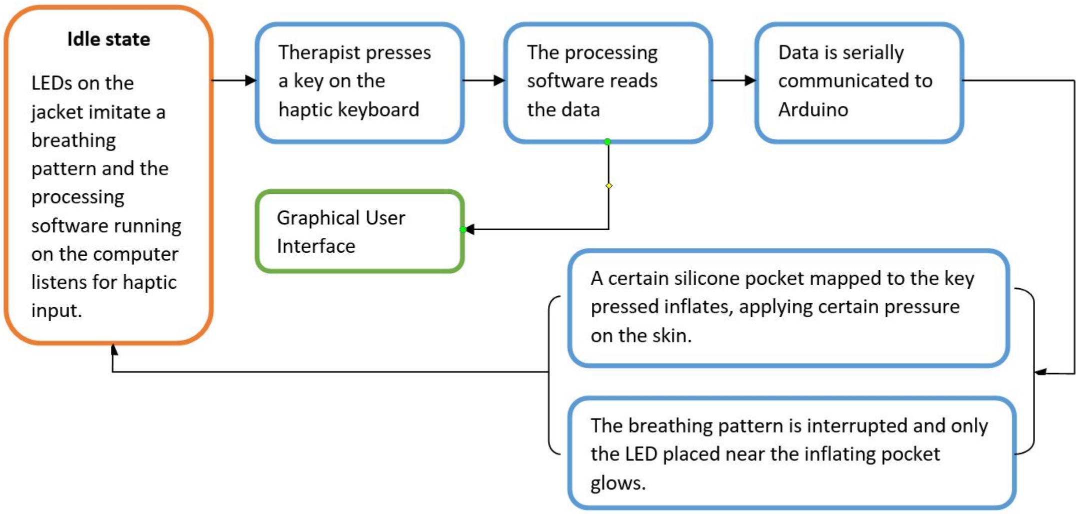


Figure 30: Flow diagram describing the working process of the design

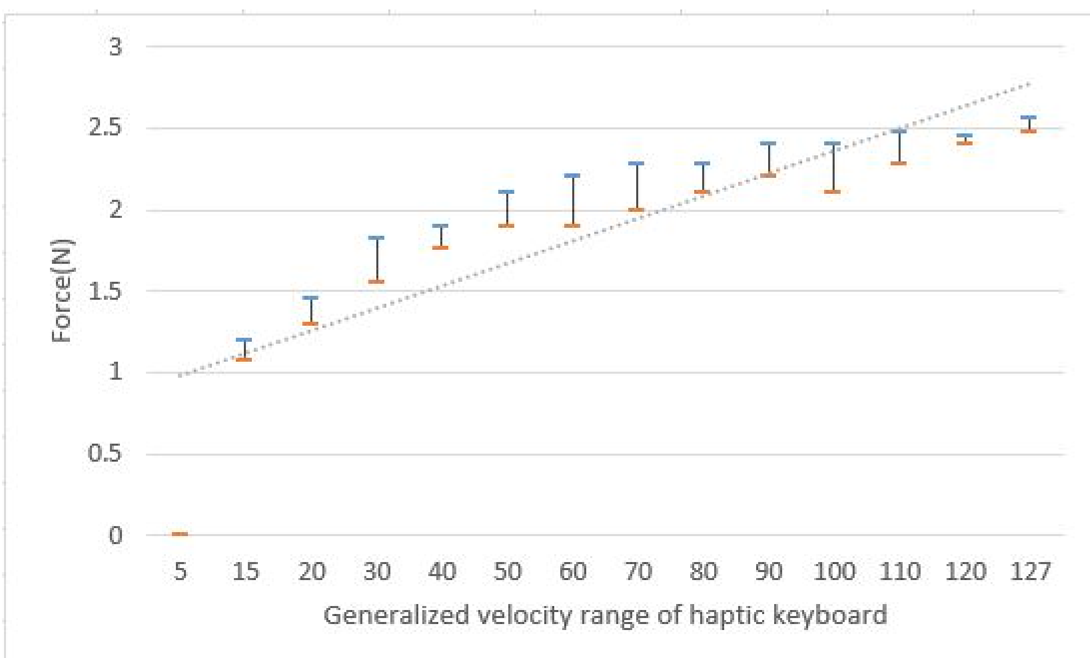


Figure 31: Graph showing range of forces recorded for a given velocity and a trend line showing increase in the average forces for the defined velocity range in ideal situation.

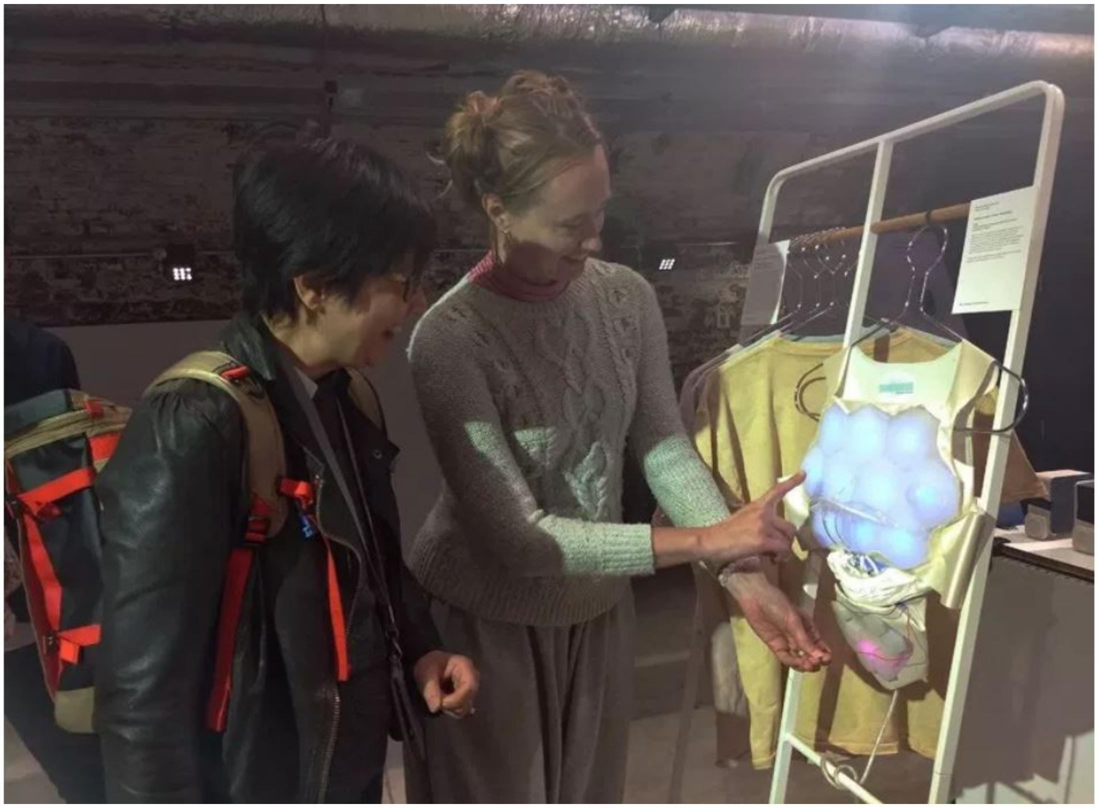


Figure 32: Flexo first iteration design presented in London Exhibition[18]

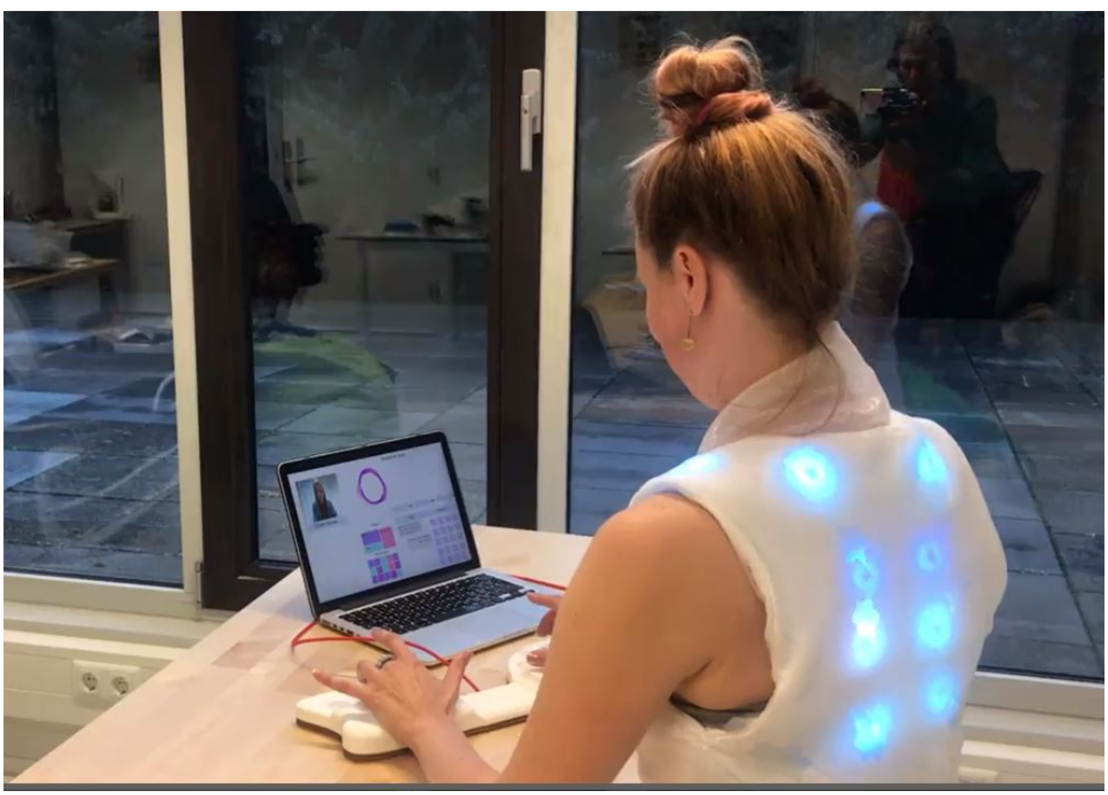


Figure 33: Kristin as a remote therapist interacting with a client over video communication

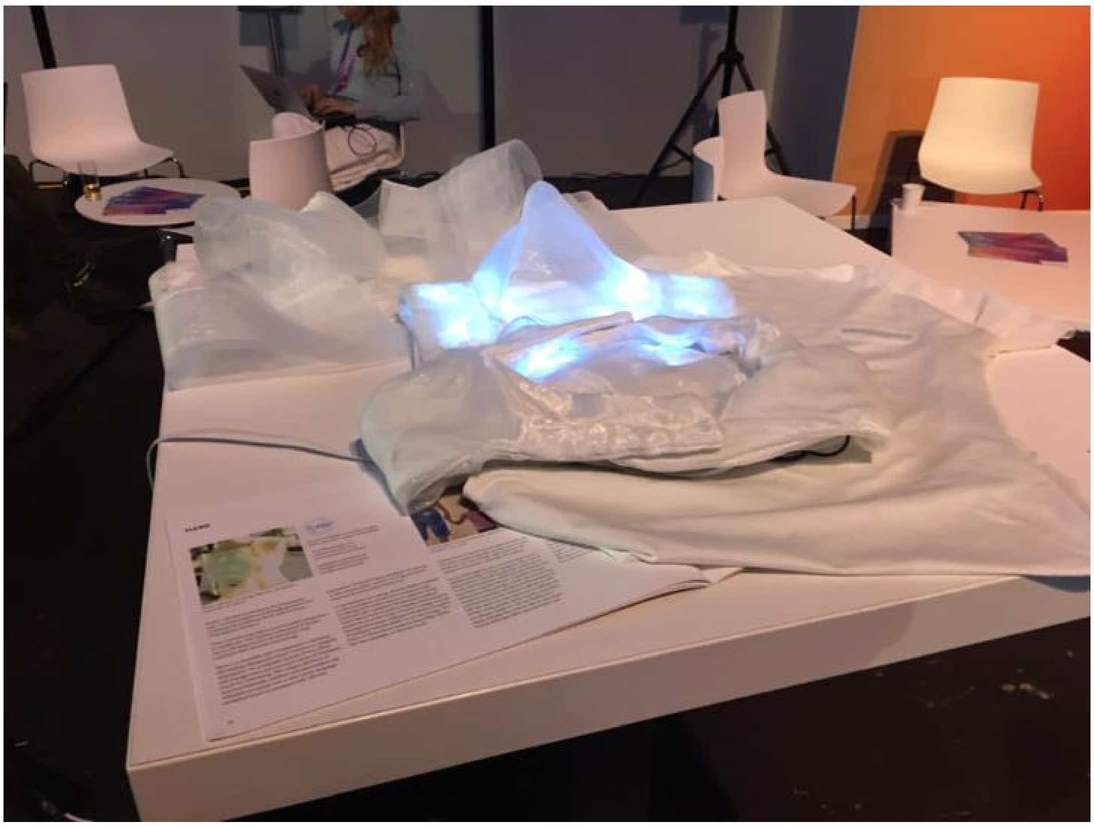


Figure 34: Flexo final design display at ICT 2018[19]

6 DISCUSSION

From figure 31, it was shown that the designed actuator pocket can be configured to different forces applied onto the skin. This not only helps in physiotherapy to define the force range as well as the levels, but can also be used for other applications or study purposes. The forces experienced by a person can be influenced by two main factors; the condition of ends of the air tube and the condition of the pocket. If the end that connected the pocket lost its silicone sealing or the end connecting the valve is not tight enough, there will be leakage of air, affecting the forces produced by the pocket. If the pocket air chamber expanded in longer use, it also influences that forces due to low inflation. Since the present pocket design's lifetime is not high enough for a long use, modular design has been chosen to facilitate quick swap of pockets when they are damaged. Other than interchangeability, modular design provide opportunities to upgrade the wearable with additional functionalities without major design changes.

On the sustainability point, it was already noted that silicone that is not biodegradable was used in the project. But, efforts has been made to reduce the use of silicone material as much as possible. The pocket pairs are connected with silicone bridges of thinner width and rather than using additional layer to add LED's to the wearable, they are placed smartly on the same silicone pocket layer. The LED's and electronics are also not integrated into the fabric, like most of the smart textile design; thus the components can be reused in other projects if needed. All these changes push towards a eco-friendly design.

7 CONCLUSION

The goal of this project is to realize a system that can mediate touch. A wearable soft exoskeleton was designed that can communicate touch using silicone pockets. The design was focused on aiding physiotherapy sessions remotely to make it more efficient and time saving. Since remote touch in this area of application is completely new, this project may act as reference for future developments.

Case studies using this wearable would provide more insight into applicability of the design in different areas, along with inputs that can improve its efficiency and usability. Real-time pressure sensing of the silicone pockets can be really helpful in replacing the damaged or defective pockets on time. A one size model is something that can be looked into, as the present design cannot fit many people; personalized wearable jackets are not a ideal solution while performing user studies.

8 ACKNOWLEDGEMENT

Thank you Kelly Van Tol, creative technology student at University of Twente for the work on LED breathing pattern and bio-sensing data and Marina Toeters, fashion technology hub for Flexo for the help in the fabric choice and design work in collaboration with Kristin Neidlinger.

9 APPENDIX

Appendix A

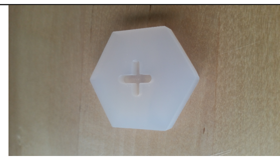
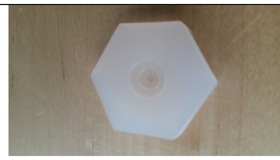
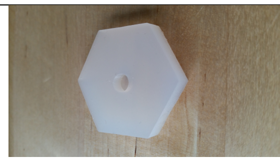
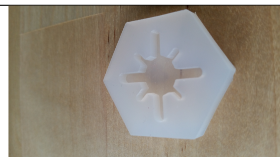
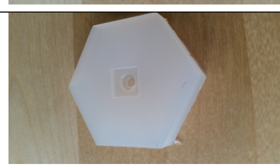
S.No.	pocket	Towards the stiff surface	Towards the skin
1		1.8	2.2.
2		2.4	1.6.
3		2.9	2.2.
4		2.9	2.1.
5		2.2	1.3.
6		4.4	2.4.
7		2.7	2.4.
8		3.3	1.9.
9		2.9	1.9.
10		1.8	1.5.

Table 2: Different pockets and the approximate forces (N) produced by them respectively

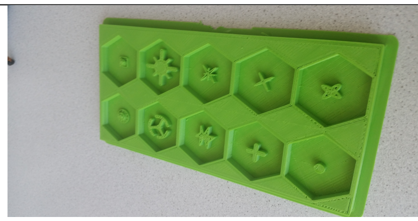
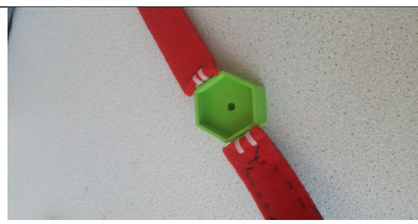
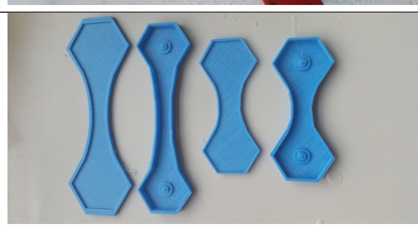
S.No.	Mold	Description
1		The mold was used to cast a silicone strip with nine pockets that was used in the second design iteration.
2		The mold was used too cast multiple pockets with different internal shapes and are used in many test studies.
3		These molds were made using laser cutting, to see if it can replace the 3D printing to reduce the production time. The outcome was not efficient and manually starting the etching process for multiple times for desired depth was not optimum.
4		The watch model was made for measuring the forces applied by different pockets on the skin but it was not successful. Since the air tube is not directly connected and sealed to the pocket, the air pressure in the chamber was not enough to inflate the pocket.
5		This is the two piece model that was used in the final iteration of the wearable design.The silicone casting was repeated multiple times to cover all nine pressure points.
6		To test the bending effect of the silicone, one of the mold from two piece model was modified and casted. The strip connecting the two pockets raised upwards a little.
7		The second mold design used in the final iteration of the wearable design. Since it can't be 3D printed with the available printers due to its large size, laser cutting was used. Rather than etching, multiple laser cut layers are glued together to form the mold.
8		It is the final mold design used for the wearable and it is a set of two pocket molds 3D printed. The molds were more that the required sets so that in a single cast, it would cover the whole design with extra pocket strips for replacement.

Table 3: Different kinds of molds used in the project

Appendix B

Force sensing resistor(FSR) from Tekscan[17] was used to measure the forces applied by the silicone pockets onto a surface. With known weights and measuring range of the sensor (0-4.4N), calibration graph has been achieved and can be seen in the figure35

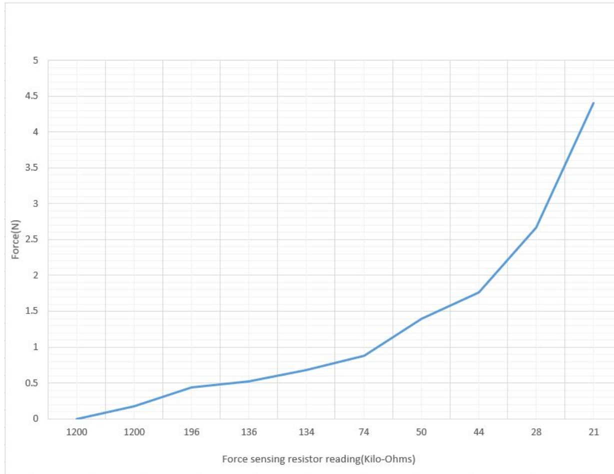


Figure 35: Pre-calibrated graph relating the FSR reading to forces

Appendix C

```
#include <Adafruit_NeoPixel.h>

#define PIN    13
#define N_LEDS 12

String str;
int val1;
int val2;
int pin[] = {2, 3, 4, 5,7, 8,9,10, 11, 12, A0,A3,A2};
int demo = A4;
int pinCount = 12;
int ledPins[] = {
  1};
Adafruit_NeoPixel strip = Adafruit_NeoPixel(N_LEDS, PIN, NEO_GRB + NEO_KHZ800);

void setup() {
  pinMode(ledPins[0], OUTPUT);
  for (int i = 0; i < 14; i++)
  {
    pinMode(pin[i], OUTPUT);
  }
  pinMode(demo, INPUT);
  Serial.begin(9600);
  strip.begin();
  long timer = millis();
}

void loop() {
  pixelColor(0,100);
  int buttonstate = analogRead(demo);
  if (Serial.available() > 0)
  {
    if (Serial.find("a")) {
      val1 = Serial.parseInt();
      val2 = Serial.parseInt();
      pump(val1, val2);
    }
  }
  else if (buttonstate == LOW)
  {

```

[17] https://www.tekscan.com/products-solutions/force-sensors/a201

```
  digitalWrite(A2, HIGH);
    digitalWrite(3, HIGH);
    wait2(1000);
    digitalWrite(A2, LOW);
    digitalWrite(3, LOW);

    digitalWrite(A3, HIGH);
    digitalWrite(4, HIGH);
    wait2(1000);
    digitalWrite(A3, LOW);
    digitalWrite(4, LOW);

    digitalWrite(A0, HIGH);
    digitalWrite(5, HIGH);
     wait2(1000);
    digitalWrite(A0, LOW);
    digitalWrite(5, LOW);

    digitalWrite(2, HIGH);
    digitalWrite(7, HIGH);
     wait2(1000);
    digitalWrite(2, LOW);
    digitalWrite(7, LOW);

    digitalWrite(11, HIGH);
    digitalWrite(9, HIGH);
    wait2(1000);
    digitalWrite(11, LOW);
    digitalWrite(9, LOW);

    digitalWrite(12, HIGH);
    digitalWrite(10, HIGH);
    wait2(1000);
    digitalWrite(12, LOW);
    digitalWrite(10, LOW);
}
}
void pump(int val1, int val2) {

  switch(val2) {
  case 49:
    light(0,1);
    digitalWrite(A2, HIGH);
    digitalWrite(3, HIGH);
    wait(val1);
    digitalWrite(A2, LOW);
    digitalWrite(3, LOW);
    break;
  case 51:
    light(2,3);
    digitalWrite(A3, HIGH);
    digitalWrite(4, HIGH);
    wait(val1);
    digitalWrite(A3, LOW);
    digitalWrite(4, LOW);
    break;
  case 54:
    light(4,5);
    digitalWrite(A0, HIGH);
    digitalWrite(5, HIGH);
    wait(val1);
    digitalWrite(A0, LOW);
    digitalWrite(5, LOW);
    break;
  case 56:
    light(6,9);
    digitalWrite(2, HIGH);
    digitalWrite(7, HIGH);
    wait(val1);
    digitalWrite(2, LOW);
    digitalWrite(7, LOW);
    break;
  case 58:
    light(7,8);
    digitalWrite(11, HIGH);
    digitalWrite(9, HIGH);
    wait(val1);
```

```
    digitalWrite(11, LOW);
    digitalWrite(9, LOW);
    break;
  case 61:
    light(10,11);
    digitalWrite(12, HIGH);
    digitalWrite(10, HIGH);
    wait(val1);
    digitalWrite(12, LOW);
    digitalWrite(10, LOW);
    break;
  }
}


void pixelColor(int l,int c) {
  wait2(300);
  int k = 0;
  int m = 0;
  for (int j = 0; j < 12; j+=2) {
    if (j == 6) {
      k = 9;
      m = 6;
    }
    else if (j == 8) {
      k = 10;
      m = 7;
    }
    else if (j == 10) {
      k = 11;
      m = 8;
    }
    else {
      k = j;
      m = k+1;
    }

    if(Serial.available()>0){
      if(Serial.find("a")){
        val1 = Serial.parseInt();
        val2 = Serial.parseInt();
        pump(val1,val2);
      }
    }
    wait2(10);
    for(int i = c; i < 200; i++) {
      if(Serial.available()>0){
        if(Serial.find("a")){
          val1 = Serial.parseInt();
          val2 = Serial.parseInt();
          pump(val1,val2);

        }
      }
      wait2(2);
      strip.setPixelColor(k, strip.Color(0, i-50, 255-i));
      strip.setPixelColor(m, strip.Color(0, i-50, 255-i));
      wait2(2);
      strip.show();

    }
    wait2(1);
  }

  wait2(300);
  for(int j = 12; j > 0; j-=2) {
    if (j == 8) {
      k = 9;
      m = 6;
    }
    else if (j == 10) {
      k = 10;
      m = 7;
    }
    else if (j == 12) {
      k = 11;
      m = 8;
```

```
    }
    else {
      k = j-2;
      m = k+1;
    }
    if(Serial.available()>0){
      if(Serial.find("a")){
        val1 = Serial.parseInt();
        val2 = Serial.parseInt();
        pump(val1,val2);

      }
    }
    wait2(10);
    for (int i = 200; i > 100; i--) {
      if(Serial.available()>0){
        if(Serial.find("a")){
          val1 = Serial.parseInt();
          val2 = Serial.parseInt();
          pump(val1,val2);

        }
      }

      wait2(2);
      strip.setPixelColor(k, strip.Color(0, i-50, 255-i));
      strip.setPixelColor(m, strip.Color(0, i-50, 255-i));
      wait2(2);
      strip.show();
    }
    wait2(1);
  }
  wait2(300);
}

void wait(int val1) {
  float time = millis();
  if (val1 < 80) {
    while (millis() < time + 500) {
    }
  }
  else {
    while (millis() < time + 2000) {
    }
  }
}

void wait2(int t) {
  float time = millis();
  while(millis() < time + t){
    if(Serial.available()>0){
      if(Serial.find("a")){
        val1 = Serial.parseInt();
        val2 = Serial.parseInt();
        pump(val1,val2);
      }
    }
  }
}

void light(int i,int j) {
  strip.setPixelColor(i, strip.Color(50, 255, 255));
  strip.setPixelColor(j, strip.Color(50, 255, 255));
  strip.show();
}
```

Listing 1: Aurdino code for pocket control and LED pattern

```
import processing.serial.*;
import themidibus.*;

Serial myPort;
String val;
MidiBus myBus;

```

```
void setup()
{
  size(200,200);

  String portName = Serial.list()[0];
  myPort = new Serial(this, portName, 9600);

  MidiBus.list();

  myBus = new MidiBus(this, "Seaboard Block", -1);
}

void draw() {
  int channel = 0;
  int pitch = 64;
  int velocity = 0;

  myBus.sendNoteOn(channel, pitch, velocity); // Send a Midi noteOn
  delay(200);
  myBus.sendNoteOff(channel, pitch, velocity); // Send a Midi nodeOff

  int number = 0;
  int value = 90;

  myBus.sendControllerChange(channel, number, value); // Send a controllerChange
  delay(2000);

}


void noteOn(int channel, int pitch, int velocity) {
  myPort.write("a" + velocity + "," + pitch);

  // Receive a noteOn
  println();
  println("Note On:");
  println("--------");
  println("Channel:"+channel);
  println("Pitch:"+pitch);
  println("Velocity:"+velocity);
}

void noteOff(int channel, int pitch, int velocity) {
  // Receive a noteOff
  println();
  println("Note Off:");
  println("--------");
  println("Channel:"+channel);
  println("Pitch:"+pitch);
  println("Velocity:"+velocity);
}

void controllerChange(int channel, int number, int value) {
  // Receive a controllerChange
  println();
  println("Controller Change:");
  println("--------");
  println("Channel:"+channel);
  println("Number:"+number);
  println("Value:"+value);
}

void delay(int time) {
  int current = millis();
  while (millis () < current+time) Thread.yield();
}
```

Listing 2: Processing code that connects the haptic device to the control system

```
import processing.video.*;

Movie movie;
Movie orb;
PImage img;
PImage img2;
```

```
boolean back = false;
float t = 0;
int time = 0;

void setup() {
  fullScreen();
  background(255);
  // Load and play the video in a loop
  movie = new Movie(this, "person.mp4");
  orb = new Movie(this, "orb.mov");
  img = loadImage("TherapistUpdate.png");
  img2 = loadImage("flexo.png");
  movie.loop();
  orb.loop();
  time = millis();
  t = orb.duration()*1000;
}

void movieEvent(Movie m) {
  m.read();
}

void draw() {

  image(img, 0, 0, width, height);
  image(movie, width/38, height/13.5, width/3.25, height/2.75);
  image(orb, width/2.7, height/13.5, width/4.5, height/2.75);
  image(img2, width/20,height/2,width/4,height/2.25);
  ellipse(width/11,height/40*22,20,20);
  if (millis() > time + t) {
    if (back == false) {
      println("reverse!");
      orb.speed(-1.0);
      back = true;
      t = orb.duration()*1000;
      time = millis();
    } else {
      orb.speed(1.0);
      back = false;
      t = orb.duration()*1000;
      time = millis();
    }
  }
}
```

Listing 3: Processing code created to represent intended Graphical User Interface

```
/*

*/

void setup()
{
  for( int i=0;i<8;i++)
  {
    pinMode(i, OUTPUT);
  }
}

void loop()
{

  PORTD = B10011111; // digital all high
  delay(1000);
  PORTD = B00000000; // digital LOW, digital
  delay(1000);
  //single valve
  PORTD = B10000010;
  delay(1000);
  PORTD = B10000001;
  delay(1000);
  PORTD = B10000100;
  delay(1000);
  PORTD = B10001000;
  delay(1000);
```

```
  PORTD = B10010000;
  delay(1000);
  PORTD = B00000000;
  delay(1000);
  //multivalve valve
  PORTD = B10000011;
  delay(1000);
  PORTD = B10001100;
  delay(1000);
  PORTD = B10010001;
  delay(1000);
  PORTD = B10001100;
  delay(1000);
  PORTD = B10010010;
  delay(1000);
  PORTD = B10000101;
  delay(1000);
  PORTD = B10001010;
  delay(1000);
  PORTD = B10010100;
  delay(1000);
  PORTD = B10001011;
  delay(1000);
  PORTD = B00000000;
  delay(1000);
  //set with low delay
  PORTD = B10011111; // digital all high
  delay(500);
  PORTD = B00000000; // digital LOW, digital
  delay(500);
  //single valve
  PORTD = B10000010;
  delay(500);
  PORTD = B10000001;
  delay(500);
  PORTD = B10000100;
  delay(500);
  PORTD = B10001000;
  delay(500);
  PORTD = B10010000;
  delay(500);
  PORTD = B00000000;
  delay(1000);
  //multivalve valve
  PORTD = B10000011;
  delay(500);
  PORTD = B10001100;
  delay(500);
  PORTD = B10010001;
  delay(500);
  PORTD = B10001100;
  delay(500);
  PORTD = B10010010;
  delay(500);
  PORTD = B10000101;
  delay(500);
  PORTD = B10001010;
  delay(500);
  PORTD = B10010100;
  delay(500);
  PORTD = B10001011;
  delay(500);
  PORTD = B00000000;
  delay(500);
  PORTD = B10011111; // digital all high
  delay(2000);
  PORTD = B00000000; // digital LOW, digital
  delay(2000);
  delay(3000);
}
```

Listing 4: Aurdino code used in the second iteration design prototype

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