The Design and Evaluation of a Dynamic Compression Vest
for Children with Autism

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in
the Graduate School of The Ohio State University

By
Jessica Diane Modlich
Graduate Program in Mechanical Engineering

The Ohio State University
2011

Master's Examination Committee:
Professor Robert Siston, Advisor
Professor Peter Rogers
Professor Jane Case-Smith
Abstract

Autism is a very common disorder among children, with approximately 1 in every 110 children diagnosed. Children with autism typically have problems processing sensory inputs correctly, which can have a negative effect on the child’s behaviors. In order to help this problem, sensory-based interventions (SI) are used. Sensory-based interventions often apply sensory input to the child to modulate the neurological response to these sensory inputs. Multiple forms of sensory based therapy interventions are used, including weighted and compression vests, which apply deep pressure to a child’s torso. Based on an understanding of sensory receptors and the somatosensory system, the effectiveness from these vests wears off after a short time period. Although there is no proven theory for the mechanism behind sensory integration, it is believed that deep pressure applied to the child travels through the dorsal column in the spinal cord which overrides pain and discomfort in another spinal column. The mechanoreceptors which sense the deep pressure rapidly adapt to this sensory input, which could explain why the effectiveness of the vest wears off after approximately 20 minutes. Applying dynamic pressure could potentially keep these mechanoreceptors continuously responding to the deep pressure, which could increase the effectiveness of the interventions. In hopes of creating a more effective way to apply compression to the trunk, we designed a dynamic compression vest.

A first prototype of a dynamic compression vest with air bladders inflated and deflated through pneumatic and control systems was designed in a senior capstone class, ME
565, but the vest did not meet many of the initial requirements. The shortcomings of the vest motivated the need for a new design that could be used to address questions associated with SI. The second prototype, which was built for this thesis, reduced the size of the components, and moved the pneumatic and electrical systems to a box on the vest. The control system was completely redesigned, with the vest controlled through LabVIEW, which made it easy to change timing and pressure parameters. Pressure feedback was included in the system which gave more accurate control than the first prototype which used a feed-forward system. This vest provided the ability change the parameters so the effects of different pressures and timing inputs could be investigated.

We performed tests to determine the correlation between the air pressure in the bladders and contact pressure applied from the vest. This contact pressure is the mechanism that is applying the intermittent compression to the child’s trunk. The vest was tested on healthy volunteers to ensure the safety of the vest before we test on children. The majority of the subjects preferred the 0.2 – 0.4 psi range compared to 0.3 – 0.5 psi, which helps establish good pressure ranges.

This vest can now be used in multiple studies to determine the effectiveness of using dynamic compression as a form of SI. The vest can also be used to determine effective levels of pressure and the amount of time the pressure should be applied.
Acknowledgments

I would like to thank my advisor Dr. Rob Siston, without his support and encouragement I probably would not have considered going to graduate school. He was always there to help me when I needed it and to answer my endless questions. I have enjoyed and learned so much in the 2 years I have worked with him.

Thanks to Dr. Peter Rogers, whose input on the design of the vest was crucial. He was always there to help me find components or troubleshoot with me the multiple times I could not get components to work. Thanks to Dr. Jane Case-Smith, who was always patient with me as I was learning the clinical side of this project. Her input from the beginning of this project was essential in understanding the problem.

I would like to thank Lynn, Pandora, and the entire staff and Easter Seal. Their support and feedback has been invaluable to this project. They have always been willing to help me, meet with me on short notice, and let me observe their classes. Without them I would not have had the opportunity to start this project, and I cannot thank them enough.

Thank you to Tony Wells and the Tony R. Wells Foundation for their support. Tony has not only provided financial support for this project for the last 2 years, but he has also provided support and feedback on the project, which has been extremely helpful.
To my NMBL labmates, thank you for all the support and feedback on my project, and most importantly for always listening to me when I got frustrated. Thank you to all of my friends and family for all of their support. And finally, to my parents and siblings who have always provided endless support and encouragement and for never letting me give up - I could not have done this without you.
Vita

May 12, 1987 ........................Born – Columbus, OH

June 2010 ................................B.S. Mechanical Engineering, The Ohio State University

June 2010-March 2011 ............Graduate Research Associate, Engineering Education

                          Innovation Center, The Ohio State University

Field of Study

Major Field: Mechanical Engineering
Table of Contents

Abstract ............................................................................................................................... ii
Acknowledgments .............................................................................................................. iv
Vita ..................................................................................................................................... vi
Table of Contents .............................................................................................................. vii
List of Tables ...................................................................................................................... x
List of Figures .................................................................................................................... xi
Chapter 1: Introduction ....................................................................................................... 1
  1.1 Autism .................................................................................................................. 1
  1.2 Sensory-Based Interventions ................................................................................. 2
  1.3 Current Static SI Devices ..................................................................................... 3
  1.4 Potential Rationale for SI .................................................................................... 6
  1.5 Opportunity for Dynamic Vest ............................................................................ 8
  1.6 Business Opportunity .......................................................................................... 9
  1.7 Focus of Thesis .................................................................................................... 10
  1.8 Significance of Research ...................................................................................... 10
  1.9 Summary of Thesis ............................................................................................. 11
List of Tables

Table 2.1: Aspects of prototype that need improvement. These are the areas that will be the focus of the new prototype. .......................................................... 25

Table 3.1: Comparison of pneumatic components from prototype 1 and prototype 2. .... 30

Table 3.2: Parts list for major components for the second prototype of the vest .......... 43

Table 3.3: Comparison of important aspects for the 2 prototypes. The focus of the second prototype was to improve upon these areas. ................................................................. 44

Table 5.1: Heart rate and oxygen level for healthy subjects during testing. These values were taken before the vest was on, and before and after interventions, and the vest did not have a major effect on the user’s heart rate or oxygen level ........................................ 60
List of Figures

Figure 1.1: Examples of current static devices on the market. a) Child wearing weighted vest b) and c) children wearing elastic compression vests (onestopsensoryshop.com, sensoryuniversity.com, especialneeds.com) ........................................................................................................... 5

Figure 1.2: Graphic of spinal tracts. The dorsal column is thought to inhibit the pain and discomfort from the spinothalamic tract. (adapted from Royal College of Surgeons in Ireland Illustrations) ........................................................................................................... 8

Figure 2.1: Design matrix for therapeutic stimulation of the vest. Air pressure was the highest ranking concept, and belts tightened by piezo material the second highest....... 15

Figure 2.2: Design matrix for energy source of vest. Rechargeable battery had the highest score, with electric outlet only around 2 points lower. ........................................ 16

Figure 2.3: Design matrix for fastening and tightening the vest. Velcro was the highest ranking concept. ........................................................................................................... 16

Figure 2.4: Sketch of the initial vest design. All of the components were designed to be on the vest, and the compartments for air pressure were designed to have partitions with air channels to minimize outward expansion. ........................................................................... 18

Figure 2.5: First prototype of vest. The vest held bladders in place, and tubing connected the bladders with the pneumatic and electrical systems which were located outside vest. ........................................................................................................... 19

Figure 2.6: Internal and external fabrics used for vest. The red internal fabric is elastic to allow for inward expansion, and the black external is stretch resistant to minimize outward expansions........................................................................................................... 20

Figure 2.7: Pneumatic diagram from prototype 1. The diaphragm pump inflated the bladders through solenoid valves, and the bladders were exhausted through other solenoid valves connected to the vacuum. There was no feedback in the system. ......................... 21

Figure 2.8: Timing diagram of the three rows, which were inflating, deflating, or holding a pressure. The inflation was done through timing and without feedback. The air pressure in the bladders was unknown. ........................................................................................................... 22
Figure 3.1: New prototype of the vest. The laptop and power source are both connected to the signal conditioning box, which is connected to the pneumatic system on the vest.

Figure 3.2: New Velcro strips added to the middle of each row in order to minimize outward expansion.

Figure 3.3: Pneumatic diagram of the second prototype. The pump inflated the bladders through solenoid valves, and pressure transducers were used to read the air pressure. The bladders were exhausted through other valves which were open to atmosphere.

Figure 3.4: Electrical circuit from vest. A power source supplied voltage to the pump and 6 solenoid valves.

Figure 3.5: Connections of the conductor cable. a) shows the wires connecting to the signal conditioning box. b) shows the 2 cables connected together and c) shows the cable going to the circuit board.

Figure 3.6: Pneumatic and electrical components on the hardware box. The conductor cable is soldered to the circuit board to provide power to the components.

Figure 3.7: Hardware box inside utility box used to protect and cover the components. The side is opened for the tubing and cable to exit the box.

Figure 3.8: Diagram of the control system connections. The DAQ card and power source are both connected to the signal conditioning box, which is connected to the hardware box through the conductor cable.

Figure 3.9: Signal conditioning box containing signal conditioning modules. On the left side there are 2 strain gauge modules for analog input for the pressure transducers. On the right side there are 7 relay modules for digital output for the pump and valves.

Figure 3.10: State diagram for 1 row of bladders within the vest. The row will enter the diagram once the current time is greater than the start time. The row will then move between inflate, hold, and deflate depending on the pressure. If the time is up or the emergency stop button is pressure, the row will deflate and exit the diagram.

Figure 3.11: The user interface for the vest in LabVIEW. Each row has individual controls and a pressure reading. LED lights are used to indicate when the row is active, and there is an emergency exhaust button for each row.

Figure 3.12: Example of user inputs for 1 row and the resulting inflation profile.

Figure 4.1: Test setup for Tekscan. The pressure sensor was placed on the torso of a mannequin, and the vest was put on over the sensor so the middle bladder came into contact with the sensor.
Figure 4.2: Pressure map recorded from Tekscan from an inflated bladder..................... 48

Figure 4.3: Graph of contact pressure applied by the vest versus the air pressure in the bladder............................................................................................................................... 50

Figure 4.4: Inflation time for 1 row for different target pressures. The time increases as the air pressure increases................................................................................................... 51

Figure 4.5: Effect of tightness of the vest on the user. The contact pressure is not affected, but the inflation time increases as the vest is loosened................................. 52

Figure 4.6: Data points for each test run which shows the spread of data for the same pressure range. .................................................................................................................. 53

Figure 5.1: First inflation sequence used for testing on healthy subjects. The inflation of the bladders we staggered starting from the top row. 2 pressure ranges were used: 0.2 – 0.4 psi, and 0.3 – 0.5 psi. ........................................................................................................ 58

Figure 5.2: Second inflation sequence used for testing on healthy subjects. Each row was inflated and held by itself. The pressure used was the preferred pressure range from the first pressure profile. ........................................................................................................ 59

Figure 5.3: Pressure level and inflation sequence preferences of the healthy subjects. The majority of subjects preferred the lower pressure, while the subjects were split on the inflation sequence. ........................................................................................................ 61
Chapter 1: Introduction

1.1 Autism

Autism is a complex developmental disorder that typically appears during the first three years of life and affects a person’s ability to communicate and interact with others (Rice, 2006). The number of children diagnosed with autism is estimated to be 1 in 110 (Rice, 2006). The main symptoms of autism include impairments in social interaction, communication, imagination, and repetitive patterns of behavior (Wing, 1996). Some examples of these symptoms could include impaired eye contact, a delay in development of or failure to develop language skills, and repetitive motor behaviors such as hand flapping or finger twisting (Baird, 2003). Children with autism can get upset by minor changes or have unusual reactions to the way things sound, smell, or feel. They also typically do not understand feelings, jokes, or sarcasm (Johnson & Myers, 2007).

Autism can be difficult to diagnose in a child, as there is no biological test for autism. It is diagnosed by observation of a child’s behaviors. The criteria for diagnosis can be difficult to define; each child presents differently (Baird, 2003). Most children are not diagnosed until 2-3 years old; once diagnosed most children begin comprehensive intervention programs (Lord, 2006).

There is no known single cause of autism, and studies suggest that a combination of genetic and environmental factors could contribute. Studies on twins show that there
is a 60% chance that identical twins both have autism, while this number is very low in fraternal twins (Baird, 2003). Even though studies show genetics have an impact on autism, there is no evidence that suggests a specific gene causes autism, and brain scans have not shown any consistent diagnostic markers. More recent studies have shown that autism is not caused by parental behaviors and there is no link between vaccines and autism (Stehr-Green, 2003).

Children with autism frequently have problems processing and responding to sensory inputs (Tomcheck & Dunn, 2007). These sensory problems can have a profound effect on children’s behaviors and development and can interfere with the children’s ability to engage in their daily activities (Provost, 2009). Some examples of sensory problems are reactions to loud sounds, reactions to the feeling of clothes, or reactions to the taste or texture of certain types of food (Johnson & Myers, 2007). Children with autism have different sensory responses depending on the individual child; one study estimated that 39% are hyposensitive, 20% are hypersensitive, and 36% show a mixed pattern of the two extremes (Greenspan & Wieder, 1997).

1.2 Sensory-Based Interventions

Sensory-based interventions (SI) are widely-used interventions that help children with autism process sensory information in an organized way. SI aims to alter underlying neurological processing of sensory information, in order to improve functional outcomes (Leong & Carter, 2008). During this intervention, trained occupational therapists provide enhanced sensory experiences (typically vestibular, tactile, or proprioceptive...
sensations) to the child to help regulate the response to sensory inputs. Interventions have been developed that apply specific sensory input believed to modulate behavioral responses to sensory stimuli. Examples of sensory-based interventions include: brushing or deep pressure applied to the body, manual compression of the joints, weighted vests, and hammocks (Stephenson & Carter, 2008).

Reportedly 38.2% of children with autism are currently using SI and 33.2% had received some form of SI in the past (Stephenson & Carter, 2008). The main support for SI comes from therapists who continue to use SI, as most studies do not support the effectiveness of SI (Leong & Carter, 2008, Watling & Dietz, 2007, Baranek, 2002). Although these studies found SI to have little or no effects, many of them had methodology problems. The results from SI studies are subjectively determined by observations, which can cause bias from the therapists or observers. Another problem is that the majority of studies were pilot studies with small sample sizes, resulting in very low power. Even though current studies do not support sensory interventions, it is still widely used in practice.

1.3 Current Static SI Devices

There are multiple devices on the market that are used to apply deep pressure as a form of sensory-based interventions to children with autism. Two types of these devices are weighted devices and compressive devices. Weighted devices are typically vests with pockets where weights can be added. Compressive devices generally apply deep pressure
through clothing made with elastic material, which are typically tightened with Velcro or straps.

Weighted options (Figure 1.1a) apply up to 10% of the child’s body weight evenly distributed throughout the vest, providing joint compression through the shoulders and spine. Therapists use weighted vests to increase trunk stability and to reduce activity levels (increase calm behavior). Many therapists believe weighted vests are effective, and they are widely used in practice. However, a review of seven studies showed that weighted vests are generally ineffective and do not have any positive effects on children’s behaviors (Stephenson & Carter, 2008). Some studies did report positive results, but these effects were low and the studies had numerous limitations, including short observation time, small sample sizes, and no interobserver reliability (Stephenson & Carter, 2008).
Devices that use compression for SI (Figure 1.1b and Figure 1.1c) generally use a latex or neoprene material and rely on the elastic properties of the material to provide a constant, static pressure, over the child’s body, by tightening the vest or by sizing the clothing too small. Instead of purchasing a compression device designed to apply SI, this compression can also be simulated using tight, elastic clothing, such as undersized Under Armour™. There is little research on the effectiveness of using compression vests, although the general perception from occupational therapists is that compression vests are superior to weighted vests. This may be due to the nature of the applied stimulation, as weights can only apply a downward force on the child’s shoulders (joint compression), while compression vests apply pressure inward on the child’s torso (deep touch).
One of the problems with both the current weighted and compression options is that children become accustomed to the pressure after a short period of time, which can vary depending on the child, and the benefits of the device decrease (Leong & Carter, 2008). The duration of time the child wears the vest depends on the therapists or parents, but vests are typically not worn all day, ranging from 20 minutes to 4 hours (Stephenson & Carter, 2008). This can be a problem at school, as teachers have more responsibilities than just for the child with autism, and they may not be able to prioritize removing the vest at the correct intervals. Most often the child wears the vest over his clothing, which can make him appear differently than the other children. Differences in appearance are generally not important to peer relationships in preschool but can become important in elementary school. As children progress to middle school, appearance becomes more important and fitting in with peers because increasingly important. Therefore beyond preschool, wearing a vest outside regular clothing is not desirable and may not be acceptable to the child.

1.4 Potential Rationale for SI

There is no confirmed clinical reason why deep pressure stimulation helps children with autism. The deep pressure is thought to stimulate mechanoreceptors in the skin that send signals up the dorsal columns in the spinal cord. These signals in the dorsal columns are thought to inhibit signals in another spinal tract, the spinothalamic tract, which carries signals of pain and discomfort (McMahon, 1981). This interaction (Figure 1.2) between the two systems relates to the phenomenon that applied pressure
overrides feelings of discomfort (McMahon, 1981) and appears to be the reason deep pressure has a calming effect on children with autism.

Pacinian corpuscles, the mechanoreceptors that sense deep pressure, rapidly adapt to an applied stimulus (Sato, 1961). They respond to the stimulus when it is first applied, but the response does not last the entire time the stimulus is applied, which could explain why the benefits from the current devices that apply a static pressure wear off after a short period of time. The pacinian corpuscles only send a signal when the pressure is first applied, but this signal diminishes over time, which may explain why the benefits of the SI wear off.
Figure 1.2: Graphic of spinal tracts. The dorsal column is thought to inhibit the pain and discomfort from the spinothalamic tract. (adapted from Royal College of Surgeons in Ireland Illustrations)

1.5 Opportunity for Dynamic Vest

Multiple problems exist with current devices that apply deep pressure as a form of SI. These devices are only effective for a short period of time, they must be removed at timed intervals throughout the day, and they are typically worn on top of a child’s
clothing. These issues create an opportunity to design a new device that addresses these issues with the current devices. Since the mechanoreceptors have a temporal component to them, using dynamic pressure may be a way to keep these receptors continuously responding to applied pressure.

Using dynamic pressure instead of using static pressure has potential benefits. First, with a dynamic vest, the amount, location, and timing of the pressure can be varied, which could potentially stimulate the mechanoreceptors more frequently, and the vest could be effective for a longer period of time. Second, since the amount, location, and timing of the pressure could be varied, a dynamic vest could be more child-specific than a static vest, as the parameters of the vest could be adapted to each child's sensory needs. This ability to customize the amount and type of pressure could be beneficial to a child with autism, as autism affects each child differently. Lastly, since the pressure can be turned on and off, a dynamic vest could be worn all day, as opposed to the static vests that need to be removed throughout the day. If such a vest does not need to be frequently donned and doffed, it can be worn discretely underneath the child's clothes.

1.6 Business Opportunity

Because deep pressure vests are widely used in practice, and research show that current vests are not always effective, a better designed vest is needed. One in every 110 children is diagnosed with autism, and the majority of these children will receive sensory-based interventions. While it is unknown how many children use weighted or compression vests, around 70% of children with autism receive or have received a form
of SI (Stephenson & Carter, 2008). Current vests are sold for $50-$250 depending on the type of vest. Given the large number of children with autism that use SI and the typically price of a vest, the market potential for a dynamic vest is very large.

1.7 Focus of Thesis

This research is a part of a larger study with the long term goal of designing and commercializing a dynamic compression vest that is more effective than the current static compression vests. Before a final vest can be built and commercialized, more research relating to the vest needs to be done. The focus of this thesis is to design and build a test bed vest that applies dynamic deep pressure to the trunk. The test bed will have the ability to change the amount, location, and timing of the pressure applied to the child’s torso. The vest will be programmed in LabVIEW with a user interface so these parameters can be easily varied while someone is wearing the vest. After the test bed is built, pressure sensors will be used to determine the amount of pressure applied when a subject is wearing the vest. The vest will then be tested on healthy volunteers, which will allow us to validate the vest and help establish baseline pressure parameters in healthy subjects. These parameters can then be used to test the vest on children.

1.8 Significance of Research

This research will work towards answering questions regarding the effectiveness of dynamic sensory-based interventions, as well as questions about the level of pressure and timing variables with SI. This test bed will give us the ability to test multiple
subjects with many combinations of parameters, which can help establish guidelines for dynamic applications of pressure as the child is wearing the vest. The test bed will also assist in the long term goal of commercializing a dynamic compression vest for children with autism.

1.9 Summary of Thesis

This thesis contains 5 subsequent chapters. Chapter 2 describes and analyzes a first prototype of a dynamic pressure vest. Chapter 3 describes the hardware and software of the second prototype. Chapters 4 and 5 present pressure testing and healthy subject testing of the vest. Chapter 6 presents conclusions and next steps.
Chapter 2: Previous Work

2.1 Introduction

A first prototype of a dynamic compression vest was designed and built by an interdisciplinary team in 2009-2010 in a senior capstone course (ME 565). The team consisted of 4 undergraduate mechanical engineers (Gregory Chernov, Jarred Kaiser, Jessica Modlich, and Shea Mogg) and 2 graduate occupational therapy students (Sarah Chafins and Laura Piper). The team was advised by Dr. Robert Siston, Assistant Professor of Mechanical Engineering, Dr. Peter Rogers, Director of the Social Innovation and Commercialization Initiative, and Dr. Jane Case-Smith, Chair of the Occupational Therapy Division.

2.2 Specification and Requirements

After talking to therapists and studying current static vests and determining their strengths and weaknesses, we defined specifications and requirements for our vest. Functionally, we wanted the vest to apply contact pressure to the torso of the child, and we wanted to vary this contact pressure in hopes the child will not habituate to the pressure. The vest needed to be easy to don and doff, and easy to operate. If the vest were too complicated, the parent or caregiver would not want to use it. Safety was a very
important concern as well, and we determined there should be a way to easily shut off the vest and release the pressure, in case the child gets over-stimulated.

The materials of the vest were also important because children with autism are particular about the look and feel of their clothing and will refuse to wear clothing which they find uncomfortable. We wanted the vest to be comfortable and made from a breathable material, as we hoped the children will be wearing this vest all day. We also needed to avoid tags and seams in the vest, as children with autism can be sensitive to these. We did not want to restrict the child’s mobility when he or she is wearing the vest, allowing the child to play and carry on a normal daily routine as if they were not wearing the vest. The vest must remain as light as possible, to reduce fatigue when wearing the vest. We set a maximum weight for our first prototype at 5 pounds, which is 10% of the body weight of an average 10 year old, with the hopes that future prototypes will weigh less than this.

We wanted the vest to be washable, since children are very active and would get it dirty easily. We discussed using a washable fabric slip that could be detachable from the mechanical components, allowing only the fabric portion to be washed. Along with being washable, the vest had to be durable in order to withstand a child’s active life. We preferred a vest that was worn under clothes, as we did not want the child to stand out from his peers, but we determined this was not mandatory for the first prototype.

Since we eventually wanted to market and sell this vest, a cost goal was set. The weighted vests currently on the market are sold for $70-$80 and since we were designing a dynamic vest that would theoretically be more effective than the current options, we could have sold it for a higher price. We set our goal to limit the cost to the consumer of our vest to
$150, thereby driving the cost of manufacturing the device to be well below $150. Since the vest will qualify as a medical device, our hope was that the cost of device would eventually be covered, at least partially, by insurance.

### 2.3 Brainstorming

Once we set the requirements for our vest, we brainstormed ideas for ways we could achieve these requirements. One of the main decisions we had was how to apply the contact pressure to the child. We had four main ideas: air pressure, belts driven by electric motors, belts driven by piezoelectric materials, and massage rollers. We used many criteria to evaluate these ideas, including size, safety, weight, comfort, and variability. We also had to determine the type of energy source that would power the vest components from an electrical outlet, a disposable battery, and a rechargeable battery. Finally we brainstormed ways to fasten and tighten the vest, as it will need to fit each child tightly in order to apply contact pressure. We evaluated many ideas including a strap, clasps, Velcro, and buttons.

In order to evaluate our ideas for the vest, we used a design matrix. We determined criteria for each category, and we assigned a ranking for each criterion based on level of importance to the team. We then evaluate each concept against the criteria, and multiplied that number by the criteria ranking. The numbers for the concepts were summed, resulting in a final score. The completed design matrix can be seen in Figure 2.1 – Figure 2.3.
<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Cost</th>
<th>Score</th>
<th>Rank</th>
<th>Concept 1: Air Pressure</th>
<th>Concept 2: Belts driven by motor</th>
<th>Concept 3: Belts tightened by Piezo</th>
<th>Concept 4: Massage Rollers</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rank</td>
<td>Score</td>
<td>Rank</td>
<td>Score</td>
<td>Rank</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>4.8</td>
<td>7.2</td>
<td>3.0</td>
<td>5.4</td>
<td>1.8</td>
<td>3.2</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>3.2</td>
<td>4.3</td>
<td>12.6</td>
<td>3.0</td>
<td>9.6</td>
<td>3.0</td>
<td>9.6</td>
<td>3.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Size</td>
<td>3.4</td>
<td>2.3</td>
<td>7.7</td>
<td>3.5</td>
<td>11.9</td>
<td>5.0</td>
<td>17.0</td>
<td>1.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Therapeutic Benefits</td>
<td>5.0</td>
<td>4.2</td>
<td>21.0</td>
<td>4.0</td>
<td>20.0</td>
<td>4.0</td>
<td>20.0</td>
<td>4.6</td>
<td>23.0</td>
</tr>
<tr>
<td>Durability</td>
<td>3.2</td>
<td>4.8</td>
<td>12.8</td>
<td>3.3</td>
<td>10.4</td>
<td>3.0</td>
<td>9.6</td>
<td>3.0</td>
<td>6.4</td>
</tr>
<tr>
<td>Speed of Response</td>
<td>2.2</td>
<td>2.5</td>
<td>5.5</td>
<td>4.3</td>
<td>9.4</td>
<td>4.0</td>
<td>8.8</td>
<td>3.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Required Power</td>
<td>2.4</td>
<td>3.0</td>
<td>7.2</td>
<td>3.3</td>
<td>7.8</td>
<td>3.5</td>
<td>8.4</td>
<td>2.8</td>
<td>6.6</td>
</tr>
<tr>
<td>Variability</td>
<td>3.2</td>
<td>4.3</td>
<td>13.6</td>
<td>3.0</td>
<td>9.6</td>
<td>3.0</td>
<td>9.6</td>
<td>3.3</td>
<td>10.4</td>
</tr>
<tr>
<td>Noise Distraction</td>
<td>3.0</td>
<td>3.2</td>
<td>9.6</td>
<td>3.3</td>
<td>9.8</td>
<td>4.8</td>
<td>14.3</td>
<td>3.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Safety</td>
<td>5.0</td>
<td>4.4</td>
<td>22.0</td>
<td>3.2</td>
<td>16.0</td>
<td>3.0</td>
<td>15.0</td>
<td>3.4</td>
<td>17.0</td>
</tr>
<tr>
<td>Accurate Control</td>
<td>3.2</td>
<td>3.4</td>
<td>10.9</td>
<td>3.5</td>
<td>11.2</td>
<td>3.8</td>
<td>12.0</td>
<td>3.3</td>
<td>10.4</td>
</tr>
<tr>
<td>Maintenance</td>
<td>2.6</td>
<td>4.3</td>
<td>11.1</td>
<td>3.6</td>
<td>7.8</td>
<td>3.0</td>
<td>7.8</td>
<td>2.3</td>
<td>5.9</td>
</tr>
<tr>
<td>Locational Flexibility</td>
<td>2.6</td>
<td>3.8</td>
<td>9.9</td>
<td>2.4</td>
<td>6.2</td>
<td>2.4</td>
<td>6.2</td>
<td>3.2</td>
<td>8.3</td>
</tr>
<tr>
<td>Weight</td>
<td>4.0</td>
<td>3.8</td>
<td>14.4</td>
<td>3.2</td>
<td>12.8</td>
<td>4.4</td>
<td>17.6</td>
<td>2.4</td>
<td>9.6</td>
</tr>
<tr>
<td>Comfort</td>
<td>4.6</td>
<td>4.6</td>
<td>18.4</td>
<td>3.4</td>
<td>15.6</td>
<td>3.8</td>
<td>17.5</td>
<td>2.2</td>
<td>10.1</td>
</tr>
<tr>
<td>Heat Dissipation</td>
<td>2.2</td>
<td>4.8</td>
<td>8.8</td>
<td>3.3</td>
<td>7.2</td>
<td>2.3</td>
<td>5.0</td>
<td>4.0</td>
<td>8.8</td>
</tr>
<tr>
<td>Number of Components</td>
<td>1.6</td>
<td>3.5</td>
<td>5.6</td>
<td>3.5</td>
<td>5.6</td>
<td>3.5</td>
<td>5.6</td>
<td>3.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Number of Specialized</td>
<td>2.0</td>
<td>4.8</td>
<td>9.5</td>
<td>3.8</td>
<td>7.5</td>
<td>2.8</td>
<td>5.5</td>
<td>2.3</td>
<td>4.5</td>
</tr>
<tr>
<td>Components</td>
<td>1.6</td>
<td>3.5</td>
<td>5.6</td>
<td>3.5</td>
<td>5.6</td>
<td>3.5</td>
<td>5.6</td>
<td>3.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Mobility</td>
<td>2.8</td>
<td>3.6</td>
<td>10.1</td>
<td>4.0</td>
<td>11.2</td>
<td>4.3</td>
<td>11.9</td>
<td>3.3</td>
<td>9.1</td>
</tr>
<tr>
<td>Breathability</td>
<td>3.6</td>
<td>3.0</td>
<td>10.8</td>
<td>2.8</td>
<td>10.1</td>
<td>2.8</td>
<td>10.1</td>
<td>3.2</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Figure 2.1: Design matrix for therapeutic stimulation of the vest. Air pressure was the highest ranking concept, and belts tightened by piezo material the second highest.
### Energy Source

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Rank</th>
<th>Score</th>
<th>Weight</th>
<th>Rank</th>
<th>Score</th>
<th>Weight</th>
<th>Rank</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>2.2</td>
<td>5.0</td>
<td>11.0</td>
<td>3.2</td>
<td>7.0</td>
<td>2.8</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturability</td>
<td>2.6</td>
<td>5.0</td>
<td>13.0</td>
<td>4.2</td>
<td>10.9</td>
<td>4.4</td>
<td>11.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>3.6</td>
<td>3.4</td>
<td>12.2</td>
<td>3.4</td>
<td>12.2</td>
<td>3.6</td>
<td>13.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attachment</td>
<td>2.2</td>
<td>3.8</td>
<td>8.2</td>
<td>3.0</td>
<td>6.6</td>
<td>3.0</td>
<td>6.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durability</td>
<td>3.2</td>
<td>3.4</td>
<td>10.9</td>
<td>3.6</td>
<td>11.5</td>
<td>3.6</td>
<td>11.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmentally Friendly</td>
<td>1.8</td>
<td>3.4</td>
<td>6.1</td>
<td>1.4</td>
<td>2.5</td>
<td>3.6</td>
<td>6.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mobility</td>
<td>3.4</td>
<td>1.0</td>
<td>3.4</td>
<td>5.0</td>
<td>17.0</td>
<td>4.8</td>
<td>16.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise/Distraction</td>
<td>3.0</td>
<td>4.0</td>
<td>12.0</td>
<td>4.2</td>
<td>12.6</td>
<td>4.2</td>
<td>12.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>4.8</td>
<td>2.2</td>
<td>10.6</td>
<td>4.0</td>
<td>19.2</td>
<td>4.0</td>
<td>19.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>3.0</td>
<td>4.0</td>
<td>12.0</td>
<td>2.5</td>
<td>7.5</td>
<td>3.0</td>
<td>9.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>4.0</td>
<td>4.6</td>
<td>18.4</td>
<td>3.4</td>
<td>13.6</td>
<td>3.0</td>
<td>12.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comfort</td>
<td>3.8</td>
<td>1.8</td>
<td>6.8</td>
<td>3.6</td>
<td>13.7</td>
<td>3.6</td>
<td>13.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Dissipation</td>
<td>2.2</td>
<td>3.2</td>
<td>7.0</td>
<td>3.2</td>
<td>7.0</td>
<td>2.8</td>
<td>6.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sustainability</td>
<td>2.0</td>
<td>3.8</td>
<td>7.5</td>
<td>2.8</td>
<td>5.5</td>
<td>3.8</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of Use</td>
<td>3.0</td>
<td>4.6</td>
<td>13.8</td>
<td>2.2</td>
<td>6.6</td>
<td>3.0</td>
<td>9.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re-usability</td>
<td>2.4</td>
<td>4.8</td>
<td>11.3</td>
<td>1.4</td>
<td>3.4</td>
<td>4.4</td>
<td>10.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life-Span</td>
<td>2.8</td>
<td>4.6</td>
<td>12.9</td>
<td>2.2</td>
<td>6.2</td>
<td>3.0</td>
<td>8.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Score</strong></td>
<td></td>
<td>177.4</td>
<td>163.1</td>
<td></td>
<td>179.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.2: Design matrix for energy source of vest. Rechargeable battery had the highest score, with electric outlet only around 2 points lower.

### Fastening/Tightening

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Concept 1: Rope (tie)</th>
<th>Concept 2: Snap</th>
<th>Concept 3: Clasp</th>
<th>Concept 4: Velcro</th>
<th>Concept 5: Buttons</th>
<th>Concept 6: Snaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>1.5</td>
<td>3.4</td>
<td>3.4</td>
<td>4.2</td>
<td>4.2</td>
<td>3.4</td>
</tr>
<tr>
<td>Comfort</td>
<td>4.8</td>
<td>3.4</td>
<td>3.3</td>
<td>4.2</td>
<td>4.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>2.6</td>
<td>4.2</td>
<td>3.3</td>
<td>4.4</td>
<td>4.4</td>
<td>3.2</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>4.2</td>
<td>2.2</td>
<td>3.4</td>
<td>3.4</td>
<td>3.4</td>
<td>3.2</td>
</tr>
<tr>
<td>Adjustability</td>
<td>4.2</td>
<td>3.4</td>
<td>3.3</td>
<td>3.4</td>
<td>3.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Safety</td>
<td>4.2</td>
<td>3.4</td>
<td>3.3</td>
<td>3.4</td>
<td>3.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Durability</td>
<td>2.6</td>
<td>3.4</td>
<td>3.3</td>
<td>3.4</td>
<td>3.4</td>
<td>3.3</td>
</tr>
<tr>
<td><strong>Score</strong></td>
<td>77.64</td>
<td>87.44</td>
<td>76.36</td>
<td>96.41</td>
<td>71.24</td>
<td>73.4</td>
</tr>
</tbody>
</table>

Figure 2.3: Design matrix for fastening and tightening the vest. Velcro was the highest ranking concept.
After evaluating our brainstorming ideas with the design matrix we decided on a final design for our vest. The design consisted of bladders that would be inflated and deflated by an air pump and controlled with a microprocessor (Figure 2.4). This would allow for contact pressure on the torso, and give us the ability to vary the amount of pressure. The vest would be tightened using Velcro straps, which would provide an easy and quick way to fit the child into the vest. We also designed the vest to be powered by a rechargeable battery so the vest could be portable.
Figure 2.4: Sketch of the initial vest design. All of the components were designed to be on the vest, and the compartments for air pressure were designed to have partitions with air channels to minimize outward expansion.

2.4 Final Prototype 1 Design

The vest was designed to be the final vest that would be sold to consumers. We realized we would not reach all the specifications in the initial prototype, but we wanted to build a prototype that could help us work towards the final vest. The prototype we built is shown in Figure 2.5. We initially designed for the components to be contained within the vest, but the components we choose were too large, so the electrical and
pneumatic systems are contained outside. The components will be powered by a laboratory power source, as opposed to a battery as initially intended.

Figure 2.5: First prototype of vest. The vest held bladders in place, and tubing connected the bladders with the pneumatic and electrical systems which were located outside vest.

The vest had six rubber bladders, three on the anterior side, and three on the posterior side, which were held in place by fabric pockets in the vest. In order to minimize outward expansion of the vest, we used a stronger fabric on the external side to resist expansion, and an elastic fabric on the internal side to allow for the pressure to expand into the torso. Figure 2.6 shows both of these fabrics on the vest.
Figure 2.6: Internal and external fabrics used for vest. The red internal fabric is elastic to allow for inward expansion, and the black external is stretch resistant to minimize outward expansions.

To inflate and deflate the bladders, we chose a Parker Hannifin miniature diaphragm pump with a flow rate of 11 L/min. To control air flow into the bladders we used solenoid valves. To simplify the system, the bladders were controlled in pairs, so the anterior and posterior bladders had the same pressure. Each pair of bladders had a pressure line connected through a valve and a vacuum line connected through another valve, and the system was connected with 1/8” ID plastic tubing. These tubes ran from the bladders in the vest to the components located outside the vest. A diagram of the system is shown in Figure 2.7.
Figure 2.7: Pneumatic diagram from prototype 1. The diaphragm pump inflated the bladders through solenoid valves, and the bladders were exhausted through other solenoid valves connected to the vacuum. There was no feedback in the system.

To control the timing of the vest inflation and deflation, we used an Arduino Mini Pro microcontroller, which was programmed in C. Each row of bladders had three different possible states: inflating, deflating, or holding a set pressure. We programmed the controller to cycle through a pattern of these three states. The timing diagram is shown in Figure 2.8. This timing can be changed, but new code would have to be downloaded to the controller after each modification, so it was not easy to vary the timing. The control was achieved with a feed-forward system, as we did not have sensors in the bladders to read the pressure. We timed how long it took to inflate the bladders, and used this time in the code.
Figure 2.8: Timing diagram of the three rows, which were inflating, deflating, or holding a pressure. The inflation was done through timing and without feedback. The air pressure in the bladders was unknown.

The pump and two of the solenoid valves required 12 volts, the remaining four solenoid valves required 6 volts, and the microcontroller required 5 volts. An electrical sub-system was built on a prototype board to provide power to all the components from the 12 volt power supply.

2.5 Prototype 1 Evaluation

While the first prototype did provide us with a good place to start, it did not meet many of our specifications. The vest did apply dynamic contact pressure that could be varied through a program. Using 2 different fabrics for the vest did reduce some of the outward expansion when the bladders were inflated. All of the components (vest,
bladders, pump, valves, and breadboard), excluding the power source, weighed 4.5 lbs, which met our weight specification of 5 lbs. Overall, the vest was very large, and the components were contained outside of the vest, which would make it difficult to test on a child.

We chose the pump based on a flow rate that would inflate the bladders in 6 seconds. Our pump, with a flow rate of 11 lpm, did inflate a bladder in 6 seconds, but because of the high flow rate we chose, the pump was very large and noisy. The pump weighed 0.5 lbs, and is 3” x 4”, which is too large to fit on the vest. In order to get a smaller pump, it would have a lower flow rate, and it would require more time to inflate the bladders. We determined inflation time was not the most crucial value and having a smaller pump that would fit on the vest would be more important.

The valves used on the vest were 3-way valves, but 1 of the openings on the valves was not used, so the valves functioned as 2-way valves. If 2-way valves had been purchased, they would have been smaller and lighter. The tubing that was used to connect the pneumatic system was 1/8” ID, which was large, and not very flexible. The pneumatic components all required different size tubing, since we did not take this into consideration when purchasing components. In order to convert tubing sizes for the components we used multiple connectors, which complicated the system. If we purchased components that required the same size tubing, the pneumatic system could have been less complicated.

The components for the vest required different voltages, ranging from 12V to 5V, which required a large electrical circuit to supply the components from the 12V power
source. If the components all required the same voltage, the electrical system could have been smaller and easily contained on the vest. Also, it would be easier to move to a battery power source if all the components operated on required voltage lower than 12V.

The control system was able to inflate and deflate the bladders at different time intervals, but it could not be easily changed and did not have any pressure feedback. The system was programmed to inflate and deflate according to time inputs, and in order to change these time inputs new code would have to be written and downloaded to the microchip. The control system did not have pressure feedback, which made it difficult to accurately control the vest. We did not know the level of pressure inside the bladders, or the amount of contact force that would be exerted when a child was using the vest. One of the main specifications we did not reach was including an emergency stop in case something was wrong during the testing. Before the vest could be tested on kids, this would need to be added to the vest.

Although we did not get the chance to test the first prototype on children, we did give a demonstration of the vest to therapists and a parent, and they gave us feedback on the vest. The parent thought his child would benefit from a dynamic vest, and it would be likely he would wear the vest for the majority of the day. He said before his child would wear it, the vest must be self-contained and the electrical circuit must be covered. The therapists also thought dynamic compression would be very helpful, while expressing concerns about making the vest more portable. They suggested making the pressure measurable, and more adjustable, as every child’s sensory needs are different, so it would be nice to be able to personalize the vest.
After building this prototype and talking with therapists we found there were still fundamental unanswered questions as to what level of pressure was therapeutic. There is no research on the amount and timing of pressure that is the most therapeutic or dynamic versus static. Therefore, it is unknown what pattern and timing of pressures would be the most beneficial. In order to help answer these questions and to work towards a final version of a dynamic pressure vest, another prototype would need to be built. From the evaluation of the first prototype, we determined important aspects of the vest that could be improved (Table 2.1). The next prototype would focus on making improvements to these aspects. Another important feature of the next prototype would be the ability to easily vary the pressure and timing parameters in order to answer some of these basic research questions. These needs motivated the design of a new dynamic compression vest.

Table 2.1: Aspects of prototype that need improvement. These are the areas that will be the focus of the new prototype.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Prototype 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of pneumatic system</td>
<td>11 LPM</td>
</tr>
<tr>
<td>Location of pneumatic system</td>
<td>Table (outside of vest)</td>
</tr>
<tr>
<td>Size of electrical system</td>
<td>7” x 6”</td>
</tr>
<tr>
<td>Location of electrical system</td>
<td>Table (outside of vest)</td>
</tr>
<tr>
<td>Required voltage</td>
<td>12 volts</td>
</tr>
<tr>
<td>Circuit Enclosed</td>
<td>No cover</td>
</tr>
<tr>
<td>Location of power source</td>
<td>Table (outside of vest)</td>
</tr>
<tr>
<td>Weight of components</td>
<td>2.69 lb</td>
</tr>
<tr>
<td>Feedback in control system</td>
<td>No feedback</td>
</tr>
<tr>
<td>Location of control system</td>
<td>Table (outside of vest)</td>
</tr>
<tr>
<td>Emergency stop</td>
<td>No emergency stop</td>
</tr>
<tr>
<td>Number of timing inputs per row</td>
<td>2</td>
</tr>
<tr>
<td>User interface</td>
<td>No user interface</td>
</tr>
</tbody>
</table>
Chapter 3: Prototype 2 Design

3.1 Prototype Focus

The focus of this thesis is to build a second prototype vest that can be used as a test bed in order to test dynamic sensory-based interventions on multiple subjects. An important aspect to the test bed will be the ability to easily change timing and pressure parameters so that we can determine which parameters are more beneficial for children with autism. Another important aspect to the prototype is working towards a final self-contained vest. The components must be lighter and smaller than the original prototype, and the majority of the components will need to be contained on the vest.

3.2 Hardware

The first prototype had the pneumatic, electrical, and control systems outside of the vest, with six tubes running from the pneumatic system to the vest. These tubes were very large and made it difficult to transport the vest and to put the vest on and off. It was also difficult to test on children, because they would have been attached to the components on a desk, and would not be able to move around. The new vest (Figure 3.1) is designed so the pneumatic components are on the vest, and the electrical and control systems are located outside the vest. There is one conductor cable running between the vest and any outside components, making it easier to use, and easier to test on children.
3.2.1 Vest and Bladders

The vest and bladders from the first prototype are being used for the second prototype since there were no major issues with them. The vest is made from two different materials, elastic rayon on the inside and strong Condura fabric on the outside. The different fabrics allow the bladders to expand more into the body to apply pressure, as opposed to expanding outward causing the vest to be more noticeable. While the fabric does help to minimize outward expansion, there is still some expansion. For the second prototype, Velcro strips were added to the middle of the compartments to help minimize this expansion, shown in Figure 3.2.
Figure 3.2: New Velcro strips added to the middle of each row in order to minimize outward expansion.

The bladders are modified blood pressure cuffs, which are sized to cover the majority of the torso. The tubing from each bladder will run down the side of the vest and connect to the pneumatic components. These bladders are sufficient for this prototype since it is a test bed, but they could potentially be redesigned for the next prototype of the vest in order to be more breathable and lightweight.

3.2.2 Pneumatic System

The pneumatic system for the first prototype did properly inflate and deflate the bladders, so the same concept was used for the second prototype. A diaphragm pump (T2-03 Compact, Parker Hannifin, Cleveland, OH) is used to inflate the bladders through 2-way solenoid valves (KSV05B-6C, Clark Solutions, Hudson, MA). Pressure
transducers (PX72-1.5GV, Omega, Stamford, CT) were added to the system to measure the air pressure in each row of bladders which can be used for feedback. A pressure regulator (AR91-005, Omega, Stamford, CT) was also added to the system to protect the transducers. The first prototype had vacuum lines that were connected to the vacuum on the pump through another 2-way solenoid valve. The second prototype does not use the vacuum; instead the valves will open to exhaust the air pressure. A diagram of the pneumatic system can be seen in Figure 3.3.

![Pneumatic diagram of the second prototype.](image)

Figure 3.3: Pneumatic diagram of the second prototype. The pump inflated the bladders through solenoid valves, and pressure transducers were used to read the air pressure. The bladders were exhausted through other valves which were open to atmosphere.

The pump and valves from the first prototype were very large and required a high amount of voltage, therefore we chose new components that were smaller and required a
lower voltage for the second prototype. This size reduction allowed the pneumatic
system to be contained on the vest. The new pump is a Parker Hannifin micro diaphragm
pump with a flow rate of 1 LPM. This is a very large reduction from the 11 LPM of the
first pump, but we decided a smaller, lighter pump was more important than having a
higher flow rate. The pump can inflate one bladder in around one minute, which we feel
is sufficient, since the pressure will likely be held for a period of time as long as 20
minutes. The new valves are from the same company (Clark Solutions) as the first
prototype valves, except they are 2-way valves instead of 3-way valves, which reduces
their size. The tubing connecting all the components has also been reduced, from 10/32”
to 5/32”. A comparison of the components from the 2 prototypes can be seen in Table
3.1.

<table>
<thead>
<tr>
<th></th>
<th>Prototype 1</th>
<th>Prototype 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Vest Weight</td>
<td>4.5 lb</td>
<td>2.75 lb</td>
</tr>
<tr>
<td>Pump Weight</td>
<td>0.5 lb</td>
<td>1.18 oz</td>
</tr>
<tr>
<td>Size</td>
<td>3”x4”</td>
<td>1.64”x1.1”</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>11 LPM</td>
<td>1 LPM</td>
</tr>
<tr>
<td>Valves Size</td>
<td>2.12” x 0.75”</td>
<td>1.25”x0.5”</td>
</tr>
<tr>
<td>Tubing Outer Diameter</td>
<td>10/32”</td>
<td>5/32”</td>
</tr>
<tr>
<td>Maximum Voltage Required</td>
<td>12V</td>
<td>6V</td>
</tr>
</tbody>
</table>

3.2.3 Electrical System

The electrical system (Figure 3.4) for the first prototype was large because the
components required different voltage levels, which required a large power source and a
large electrical circuit to reduce the voltage from the initial 12 volts. All of the
components for the second prototype can run off a 6 volt supply, which reduces the size of the electrical system. The components are still powered by a lab power source in the current prototype, but since the required voltage is lower, it will be easier to eventually move to a small battery source.

![Electrical Circuit Diagram](image)

Figure 3.4: Electrical circuit from vest. A power source supplied voltage to the pump and 6 solenoid valves

Two connected 10 feet long printer cables (Figure 3.5) are used to connect the pneumatic components on the vest to the power source and computer. One end of the first cable was soldered into the circuit board with the pneumatic components; the other end was connected to the second cable. The end of the second cable was in screw terminals in the signal conditioning box, which will be discussed in more detail later. We chose printer cables because they are thin, have multiple conductor wires, and they already have ends that can be easily connected and disconnected. This makes it easier to transport the system, and more importantly, gives a way to quickly disconnect someone who is wearing the vest from the computer and power source.
The printer cable was small and easy to use, but it was also difficult to get the proper power through the cable to the components. The length of the cable, and the size of each individual wire, gauge 26, resulted in a 30% voltage drop from the power source. In order to supply the components with the required 6 volts, the power source needs to supply 9 volts. Another issue was supplying enough current to the components. The maximum number of components that would be powered at one time is 3 valves and the pump. These 4 components draw 0.7 amps from the power source at 9 volts. The valves initially were connected with individual hot wires and a common ground wire from the conductor cable. In order to provide the required 0.7 amps to power the devices, the valves were given individual ground wires and 3 of them were given an additional hot wire to increase the current through the conductor cable.
3.2.4 Hardware Box

The pneumatic components are contained in a box (Figure 3.6), which will be connected to the vest. The box is 4.25”x4”x2” and is enclosed in a plastic utility box (Figure 3.7) to protect the components and circuit board. The bottom of the box is a circuit board, which connects the wires from the components to the conductor cable. The pressure transducers are soldered to the circuit board and the 3 exhaust valves are also secured to the circuit board. A piece of Plexiglas is connected at a right angle to the circuit board, which contains the remaining components: diaphragm pump, 3 valves, pressure regulator, and manifold. The tubing comes out of the side of the box and runs to a fitting that tees the line into the front and back bladder for each row.
Figure 3.6: Pneumatic and electrical components on the hardware box. The conductor cable is soldered to the circuit board to provide power to the components.
3.3 Software

The main goal for the vest software is to include multiple parameters for timing and pressure so the vest can be programmed to apply any desired pressure profile. We wanted to be able to easily change these parameters within the program’s user interface, compared to the first prototype which required new code to be downloaded. We used National Instruments’ LabVIEW to control the vest, which allows us to quickly and easily change parameters in a user-interface. A diagram of the control system, showing the connections, can be seen in Figure 3.8.
3.3.1 Closed Loop Feedback

An important change from the initial prototype was the addition of the ability to acquire feedback on the amount of pressure within each bladder. Pressure transducers (PX72-1.5GV, Omega, Stamford, CT) were used to measure the air pressure, which required data acquisition. Signal conditioning modules (SC-2345, National Instruments, Austin, TX) (Figure 3.9) were used to collect analog input data from the transducers and to supply digital output to the valves and pump. The modules (SCC-SG24, National Instruments, Austin, TX) for the transducers provided a regulated 10V supply to the transducers and used a 1.6 kHz low pass filter on the signal. The transducers can be
powered with any regulated voltage supply under 10V, and 10V was used because the module provided the regulated supply. This voltage can be smaller on future prototypes that are powered from a battery. A relay module (SCC-RLY01, National Instruments, Austin, TX) used to switch the valves and pump on and off. The relay module does not provide power to the components, so the valves and pump were powered from the external power source. A shielded 68-pin cable connects the signal conditioning box to a DAQ Card (6062E, National Instruments, Austin, TX) in a laptop.
3.3.2 LabVIEW Program

The main goal of the LabVIEW program was to have the ability to vary the amount of pressure in each bladder and timing parameters for the entire system, as the optimum levels for these values are currently unknown for sensory-based interventions. Since LabVIEW has a user interface, and the vest is always connected to LabVIEW, the parameters can be easily and quickly changed without needing to download code with
each modification. This makes it easier to vary these parameters in the middle of a testing period, which will be important as we test subjects to determine the effectiveness of different parameters.

Each row of bladders in the vest is controlled independently within LabVIEW and can be programmed to a pressure profile with timing and pressure inputs. A state diagram for 1 row can be seen in Figure 3.10. The row of bladders can be either active or inactive, which is determined by the timing inputs. There are 4 timing inputs for each row: 3 start times and 1 hold time. When the current time reaches a desired start time, the row will be active, and remain active for the set hold time, otherwise the row is inactive. If the row is inactive the exhaust valve is open so any air in the bladders can exhaust. If the row is active, it can be in 1 of 3 states: inflating, holding, or deflating, which is determined by the pressure inputs. If the pressure reading from the transducer is below the set pressure range, the valve will be open and the bladders will inflate. If the pressure is within the set range, both valves will be closed and the pressure will hold. If the pressure is above the set range, the exhaust valve will open and the pressure will be released. This cycle continues as long as the row is in the active state. This allows the pressure in the bladders to adjust itself if there is a leak or if the pressure is over the set limit.

For safety, each row has an emergency exhaust button on the user interface. Once this button is pressed, the program will exit the main loop, the pressure valve will close, and the exhaust valve will open. This exhaust button is important in case the transducer
is not reading correctly, or there is another error in the system, and the pressure needs to be released.

Figure 3.10: State diagram for 1 row of bladders within the vest. The row will enter the diagram once the current time is greater than the start time. The row will then move between inflate, hold, and deflate depending on the pressure. If the time is up or the emergency stop button is pressed, the row will deflate and exit the diagram.

3.3.3 User Interface

The user interface (Figure 3.11) in LabVIEW allows the user to control the vest and to change a majority of the variables. The timing variables and the pressure reading for each row are on the right side of the interface. The left side has the emergency exhaust for each row, as well as a button to close all the valves if the program is manually stopped before completion. The pump is currently controlled by a switch on the user
interface, so it can be easily turned on and off during the program. The pressure levels are not set in the user interface; they are set within the code, due to the way the program is structured.

Figure 3.11: The user interface for the vest in LabVIEW. Each row has individual controls and a pressure reading. LED lights are used to indicate when the row is active, and there is an emergency exhaust button for each row.

An example of an inflation profile and the corresponding user input values for 1 row is shown in Figure 4.12. This example shows the row turning on at minutes 1, 8, and 15. The row was held on for 5 minutes each time. The target pressure was set at 0.5 – 0.6 psi.
Figure 3.12: Example of user inputs for 1 row and the resulting inflation profile.

3.4 Final Prototype 2

The second prototype of the dynamic compression vest has smaller components than the first prototype, and included pressure feedback to provide better control of the system. A parts list for the major components can be seen in Table 3.2.
Table 3.2: Parts list for major components for the second prototype of the vest

<table>
<thead>
<tr>
<th>Description</th>
<th>Company (Part Number)</th>
<th>Quantity</th>
<th>Price</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bladders</td>
<td>Perma-Type Rubber (special order)</td>
<td>6</td>
<td>$47.25</td>
<td>$283.50</td>
</tr>
<tr>
<td>Diaphragm Pump</td>
<td>Parker Hannifin (T2-03 Compact)</td>
<td>1</td>
<td>$95.00</td>
<td>$95.00</td>
</tr>
<tr>
<td>Solenoid Valves</td>
<td>Clark Solutions (KSV05B-6C)</td>
<td>6</td>
<td>$9.18</td>
<td>$55.08</td>
</tr>
<tr>
<td>Pressure Transducers</td>
<td>Omega (PX72-1.5GV)</td>
<td>3</td>
<td>$40.00</td>
<td>$120.00</td>
</tr>
<tr>
<td>Pressure Regulator</td>
<td>Omega (AR91-005)</td>
<td>1</td>
<td>$40.00</td>
<td>$40.00</td>
</tr>
<tr>
<td>Manifold</td>
<td>McMasterCarr (5306K32)</td>
<td>1</td>
<td>$9.55</td>
<td>$9.55</td>
</tr>
<tr>
<td>Conductor Cable</td>
<td>McMasterCarr (7925K64)</td>
<td>2</td>
<td>$7.98</td>
<td>$15.96</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>619.09</strong></td>
</tr>
</tbody>
</table>

Table 3.3 revisits the focus areas determined through evaluation of the old prototype, and compares the 2 prototypes. Out of the 12 aspects we wanted to focus on for the new design, we made improvements in 10 of them. We reduced the size and moved multiple systems to the vest, as well as increasing the control in the system. The only 2 that were not completely met were moving the location of the power source and the control system. The required voltage was decreases, which will make it easier to eventually move to a battery power source. The location of the control system was not moved because of the added control that using LabVIEW provided us. This control will make it possible to test multiple children with multiple parameters.
Table 3.3: Comparison of important aspects for the 2 prototypes. The focus of the second prototype was to improve upon these areas.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Prototype 1 (ME 565)</th>
<th>Prototype 2 (My Thesis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of pneumatic system</td>
<td>11 LPM</td>
<td>1 LPM</td>
</tr>
<tr>
<td>Location of pneumatic system</td>
<td>Table (outside of vest)</td>
<td>Box on vest</td>
</tr>
<tr>
<td>Size of electrical system</td>
<td>7” x 6”</td>
<td>4”x2”</td>
</tr>
<tr>
<td>Location of electrical system</td>
<td>Table (outside of vest)</td>
<td>Box on vest</td>
</tr>
<tr>
<td>Required voltage</td>
<td>12 volts</td>
<td>6 volts</td>
</tr>
<tr>
<td>Location of power source</td>
<td>Table (outside of vest)</td>
<td>Table (outside of vest)</td>
</tr>
<tr>
<td>Weight of components</td>
<td>2.69 lb</td>
<td>0.94 lb</td>
</tr>
<tr>
<td>Feedback in control system</td>
<td>No feedback</td>
<td>Pressure feedback</td>
</tr>
<tr>
<td>Location of control system</td>
<td>Table (outside of vest)</td>
<td>Table (outside of vest)</td>
</tr>
<tr>
<td>Emergency stop</td>
<td>No emergency stop</td>
<td>Emergency stop on user interface</td>
</tr>
<tr>
<td>Number of timing inputs per row</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>User interface</td>
<td>No user interface</td>
<td>User interface in LabVIEW</td>
</tr>
</tbody>
</table>
Chapter 4: Force and Contact Pressure Evaluation

4.1 Testing Objectives

The mechanoreceptors in the body that are activated SI sense contact pressure, and these mechanoreceptors adapt rapidly to the signal, which is the basis for designing a dynamic compression vest. Since the pressure from the vest is the mechanism that applies the SI, it would be useful to measure the level of pressure, and to use this pressure as feedback in the system. Miniature force transducers or load cells could be attached to the inside of the vest and used to measure the force between the vest and the user. Sensors that could be used range from $200 - $500 each, and 3 sensors would be needed to measure the force from each row. Since the goal of this vest is commercialize it, cost of components must be considered, and having sensors near a thousand dollars would make the price of the vest very expensive. Pressure transducers that measure the air pressure inside the bladders are less expensive, around $40 for 1 sensor. The air pressure measured from these transducers could be used as feedback in the system, which would be less expensive than force transducers, but the contact pressure applied to the user would still be unknown. We chose to use the cheaper pressure transducers in the vest, and in order to determine the contact pressure, we used a pressure sensor to measure the contact pressure and then correlate this pressure to the pressure inside the air bladders.

We hoped the contact pressure applied by the vest would be consistent, so that after measuring it, and determining the relation to the air pressure, we would be able to
know the contact pressure by measuring the air pressure. Through the multiple tests we ran, we had 3 main objectives:

1. Determine the correlation between the air pressure inside the bladders to the contact pressure that the vest applies.

2. Determine the time it takes to inflate the bladders to the maximum contact pressure.

3. Determine how the tightness of the vest affects the contact pressure applied.

4.2 Methods

To collect pressure data we used Tekscan (Tekscan, Inc., South Boston, MA), which uses a thin flexible tactile sensor to measure pressure. The sensor is attached to a handle that connects to the computer which collects and records dynamic pressure applied to the sensor. These recordings can be analyzed in multiple different pressure and force variables, versus time and location on the sensor. Before the sensor can be used, it must be calibrated by applying a known weight over the sensor. The sensor used in this testing was calibrated with a 9 lb weight.

The sensor was taped to a mannequin (Figure 4.1) and the vest was put on the mannequin and placed over the sensor. The sensor was positioned under the anterior middle bladder. Three different types of tests were run. For these tests pressure ranges of 0.1 psi were used, since keeping a bladder at 1 exact pressure is difficult. The tests were run 4 times for each pressure range in order to determine the consistency. An example of the pressure map that Tekscan recorded is shown in Figure 4.2.
Figure 4.1: Test setup for Tekscan. The pressure sensor was placed on the torso of a mannequin, and the vest was put on over the sensor so the middle bladder came into contact with the sensor.
For the first test, the bladder was inflated and held at the pressure range, and data was collected for 10 seconds. The pressure ranges tested were from 0.1 – 0.7 psi in intervals of 0.1 psi, giving 6 different ranges. We chose these ranges because this is the full pressure range of the vest, as the pump will not inflate the bladders much higher than 0.7 psi. The vest cannot accurately control below 0.1 psi because of the pressure transducers. We chose intervals of 0.1 psi because the control system in the vest cannot hold the bladders at an exact pressure, and this is the smallest interval that can be accurately held. This test was run in order to correlate the air pressure in the bladder to the force and contact pressure on the mannequin.

For the second test, the bladder started at 0 psi, and was inflated to the pressure range, and data was collected until the pressure range was reached. The pressure ranges tested were from 0.2 – 0.7 psi in intervals of 0.1 psi, giving 5 different ranges. We measured time to peak force from 0 psi. This test was run to tell how long it will take the
bladder to inflate to a given pressure. This will help us determine if the pump is good enough to inflate the vest.

For the third test, we evaluated the effect of the tightness of the vest on the mannequin. Since the vest has Velcro straps, it can be tightened to different circumferences, and we thought this might affect the contact pressure. We tested at 1 pressure range, 0.5 – 0.6 psi, and 3 different circumferences on the mannequin. We measured contact pressure and time to peak force from zero. This test was run to show us if increasing the tightness of the vest also increased the contact pressure.

4.3 Results and Discussion

The results from the first test show the contact pressure has a possible linear relationship with the air pressure inside the bladder (Figure 4.3). Adding a linear trendline through the data shows the pressures are related by the equation:

\[
\text{contact pressure} = 3.075 \times (\text{air pressure}) + 2.611
\]

This equation could be used to determine the contact pressure for a given air pressure when testing the vest in the future. We also fit a 4th order polynomial through the data passing through the origin, since there should be no contact pressure if there is no air pressure. While the polynomial does give an equation starting at zero, we will never be able to accurately control the vest below 0.1 psi due to the capabilities of the pressure transducers. The vest will be controlled between 0.1 and 0.7 psi, so using the linear trendline to determine the contact pressure is adequate, since we will not need to know the contact pressure at the extremes.
The second test showed that as the set air pressure increases, so does the time it takes for the bladder to reach maximum force (Figure 4.4). Since we reduced the size, and therefore the flow rate, of the pump for this prototype, we knew the inflation time would be reduced. At the maximum pressure tested, 0.6 psi, it took less than 45 second to inflate the bladder. This inflation time will be sufficient for the vest, and shows the trade-off for a smaller pump was a good decision. This data can also be fitted with a linear line or a 2nd order polynomial. Since the vest is controlled with pressure feedback, it would not matter which equation was used to determine inflation time, as the number will not be used to control the vest.
Figure 4.4: Inflation time for 1 row for different target pressures. The time increases as the air pressure increases.

The third test showed that the tightness of the vest does not affect the contact pressure the vest applies for a given air pressure, but it does affect the inflation time (Figure 4.5). The top graph in Figure 4.5 shows the contact pressure is fairly constant, regardless of how tight the vest it. The bottom graph shows that as you increase the tightness, the inflation time decreases. The pressure inside the bladder, that is then transferred to the outside, does not depend on the tightness, because this pressure is used for feedback in the system, and the system will correct itself to be at the set pressure. Since this pressure does not depend on the tightness, the contact pressure it applies will also not depend on the tightness. If the vest is loose, it creates more room for the bladder
to expand, and therefore takes more air to reach the set pressure. Since it takes more air to reach the pressure, it increases the inflation time. It is important that the tightness does not affect contact pressure, because we will not have to tighten the vest to the exact level each time we put it on a child. We can apply the vest to fit each child comfortably, and we will still be able to know the contact pressure.

![Graph showing the effect of tightness of the vest on contact pressure and inflation time](image)

Figure 4.5: Effect of tightness of the vest on the user. The contact pressure is not affected, but the inflation time increases as the vest is loosened.
While the results were fairly consistent for multiple tests at the same pressure, there was some variability. Figure 4.6 shows the multiple inflation times measured for each pressure level, which shows the spread of the data. There are multiple factors that could explain this spread in data, including the way the test was set up and the way the system is set up.

Figure 4.6: Data points for each test run which shows the spread of data for the same pressure range.

One factor could be that we inflated the bladders to a pressure range, not an exact pressure. The pressure could have been at the lower end of this range for 1 test, and at the higher end for another, which would give different results. The reason the bladders
were inflated to a range was because it is very difficult to get the pressure to remain at an exact pressure. As the valves close to hold the pressure in the bladder, a small amount of air might leak, which would decrease the pressure. Another reason it is difficult to hold at an exact pressure is the delay from the pressure reading from the transducers. In order to have the ability to hold at a smaller range, and therefore have more consistent results would be to improve the components. This would likely cause the cost of the vest to increase, which would most likely not be worth the increase in control.

Another factor that could have contributed to the spread in data for the test where the bladder was inflated from 0 psi is that a vacuum was not used. While we tried to exhaust all of the air from the bladder, it is difficult to completely remove all the air. For each trial ran, there could have been a different amount of residual air in the bladder, which would affect the inflation time. While adding a vacuum would increase the consistency of the results, it would increase the complexity and size of the pneumatic system. Since the results did not have a high amount of inconsistencies, the added vacuum would most likely not be worth the complexity it would cause.

The pressure testing with Tekscan was done to determine 3 objectives:

1. Determine the correlation between the air pressure inside the bladders to the contact pressure that the vest applies.

   The air pressure inside the bladders can be correlated to the contact pressure, and there is a linear relationship between these two values for the pressures tested.
2. Determine the time it takes to inflate the bladders to the maximum contact pressure.
   It took just over 20 seconds to inflate to 0.2 – 0.3 psi, the lowest pressure range we tested. This time will constantly increase as the target pressure is increases.

3. Determine how the tightness of the vest affects the contact pressure applied.
   The tightness of the vest does not affect the contact pressure applied; it only increases the inflation time.

These results will be useful when we test the vest on children. We can determine the amount of contact pressure applied to the users torso, which is helpful since this is the pressure that is applying the SI. The tests also showed that this contact pressure is not depended on the tightness of the vest, so we will not have to worry about inconsistency in results from varying the tightness.
Chapter 5: Healthy Subject Testing

5.1 Testing Objectives

While the test bed vest was designed in order to run multiple tests on children with autism to determine the effectiveness of dynamic SI, we decided to test the vest on healthy volunteers first. These tests were used to verify the safety of the vest and to help establish pressure ranges for the vest. Since the amount of pressure applied from static devices is unknown, we did not have any guidelines on the amount of pressure that would be comfortable. Testing different pressure levels with the vest on healthy subjects can give us baseline pressure data. While the pressure levels from healthy subjects might not directly correlate to children with autism, these tests will establish a good range to use when we begin testing on children.

5.2 Methods

The vest was tested on healthy subjects with multiple pressure and timing parameters in order to get their feedback on the vest. Informed consent was obtained for 5 healthy male volunteers (age 31.2 ± 15.1 years). The vest was put on the subject, and it was tightened so it would fit comfortably. During the testing period, the vest was inflated 3 different times for 12 minutes each. Each time the vest was on, we ran a program with different pressure and timing inputs. The first 2 programs had the same inflation sequence, with different levels of pressure. The bladders were held at a constant pressure
at the same time, and the inflation timing was staggered starting with the top row, moving down to the bottom row, which can be seen in Figure 5.1. Profile A was tested with this inflation profile at 0.2 – 0.4 psi, and profile B was tested with this inflation profile at 0.3 – 0.5 psi. Pressure ranges of 0.2 psi were used because it is difficult to inflate a bladder to an exact pressure or a smaller range. While each program was running, we measured heart rate and oxygen level using a pulse oximeter every 3 minutes, as well as asking the subject if they noticed the pressure and if it was uncomfortable. Taking the vitals gave us a measure to see if the body was responding normally to the vest. Asking if the subject could notice the pressure was a way to determine if their body had accommodated to the pressure and could no longer feel it. Asking the subject if the vest was uncomfortable was a check to make sure the subject was ok and not in any pain.
After we ran the 2 programs on the subject, we asked the subject which of the 2 they preferred. A third program was run with a different inflation sequence, but with the preferred pressure from the first 2 programs. The bladders were inflated and held constant one at a time for 4 minutes each, as is shown in Figure 5.2. During this program the subjects’ vitals were taken and the same questions were asked every 3 minutes. After we ran all 3 programs, we asked the subject which program they preferred. We also asked them to describe how the pressure felt when the bladders were inflated.
Figure 5.2: Second inflation sequence used for testing on healthy subjects. Each row was inflated and held by itself. The pressure used was the preferred pressure range from the first pressure profile.

5.3 Results and Discussion

The tests on healthy subjects showed us the vest was safe, and helped to establish useful pressure ranges. During the tests, the subjects were not in any pain nor were they uncomfortable. Table 5.1 shows the heart rate and oxygen level for the healthy subjects during the testing. The subject’s vitals did not vary greatly during the testing, which helps support the safety of the vest. All of the subjects completed the testing, and there were not any problems with the functionality of the vest. This helps validate that the vest is safe, and it would be safe to test on children.
Table 5.1: Heart rate and oxygen level for healthy subjects during testing. These values were taken before the vest was on, and before and after interventions, and the vest did not have a major effect of the user’s heart rate or oxygen level.

<table>
<thead>
<tr>
<th></th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
<th>Subject 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart Rate Before Vest</td>
<td>72</td>
<td>78</td>
<td>63</td>
<td>52</td>
<td>84</td>
</tr>
<tr>
<td>Program 1 Before</td>
<td>75</td>
<td>75</td>
<td>63</td>
<td>62</td>
<td>83</td>
</tr>
<tr>
<td>After</td>
<td>75</td>
<td>75</td>
<td>64</td>
<td>55</td>
<td>82</td>
</tr>
<tr>
<td>Program 2 Before</td>
<td>77</td>
<td>78</td>
<td>62</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>After</td>
<td>78</td>
<td>79</td>
<td>64</td>
<td>66</td>
<td>82</td>
</tr>
<tr>
<td>Program 3 Before</td>
<td>78</td>
<td>83</td>
<td>67</td>
<td>58</td>
<td>80</td>
</tr>
<tr>
<td>After</td>
<td>75</td>
<td>82</td>
<td>61</td>
<td>60</td>
<td>78</td>
</tr>
<tr>
<td>Oxygen Level Before Vest</td>
<td>95</td>
<td>97</td>
<td>98</td>
<td>98</td>
<td>96</td>
</tr>
<tr>
<td>Program 1 Before</td>
<td>95</td>
<td>97</td>
<td>97</td>
<td>98</td>
<td>97</td>
</tr>
<tr>
<td>After</td>
<td>95</td>
<td>96</td>
<td>96</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>Program 2 Before</td>
<td>96</td>
<td>97</td>
<td>97</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>After</td>
<td>95</td>
<td>96</td>
<td>97</td>
<td>98</td>
<td>97</td>
</tr>
<tr>
<td>Program 3 Before</td>
<td>96</td>
<td>96</td>
<td>98</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>After</td>
<td>97</td>
<td>96</td>
<td>98</td>
<td>96</td>
<td>97</td>
</tr>
</tbody>
</table>

The majority of the subjects felt neutral to the pressure; they did not like it, and they did not dislike it. One subject did like the pressure and thought it was relaxing while the vest was on. When the vest was turned on, the subjects responded that they could feel the pressure for the whole testing period, which is good because one of the main reasons for intermittent pressure is that the effect of the pressure will not wear off. One subject commented that the vest felt like he was wearing a shirt that was too small. Currently, children will wear an elastic shirt that is small so it will apply contact pressure, so our vest might be recreating this feeling.

Figure 5.3 shows the preferences for the pressure and inflation sequence for the healthy subjects. 80% of the subjects preferred the lower pressure range, 0.2 – 0.4 psi compared to the higher range, 0.3 – 0.5 psi. There was no clear preference for the
inflation sequence. This shows the effective inflation sequence might depend upon the user.

![Pressure Level Preference and Inflation Sequence Preference](image)

**Figure 5.3:** Pressure level and inflation sequence preferences of the healthy subjects. The majority of subjects preferred the lower pressure, while the subjects were split on the inflation sequence.

Two subjects commented that they could feel the pressure on the top of the vest more than on the bottom. This could be explained by the location of the pressure on the body. On the top of the torso, the vest applies pressure to the ribs, which provide more resistance, as opposed to the bottom of the torso which applies pressure to the abdomen. The abdomen does not have any bony structures and has more soft tissue, so there is not as much resistance to the pressure, so it might be more difficult to feel the pressure.

Three subjects also commented that it was a little difficult to take deep breaths at the higher pressure. The subjects were all able to breathe normally, but said the vest was
a little restrictive. This might show that the higher pressure range, 0.3 psi – 0.5 psi, might be close to the upper threshold of pressure. This information will be useful when we start testing the vest on children, as we might want to avoid this pressure range.

We needed to test on healthy subjects in order to validate safety before we test on children. While we did not receive completely positive responses from the subjects, we also did not receive negative responses. This vest was designed for children with autism, and we tested the vest on a population that it was not intended for. Children with autism are sensory seeking, and want the deep pressure applied. Healthy subjects might not have this sensory seeking behavior, so they would not like deep pressure.

Another explanation for healthy subjects not liking the pressure could be due to the neurological reasoning behind SI. The response to the deep pressure travels up the dorsal column in the spinal cord, and is believed to inhibit pain and discomfort in the spinothalamic tract (McMahon, 1981). Deep pressure in the dorsal column could always have a comforting effect, or it might only be comforting if there is discomfort in the spinothalamic tract to override. During the testing the subjects were sitting doing homework, so they most likely were not experiencing any pain, and therefore there would be no signal in the spinal column for the deep pressure to inhibit.

Overall the testing on healthy subjects was informative and helpful. There were not any issues with the hardware on the vest or with the control system. The subjects also said the vest did not cause any pain. This shows that the vest is safe to test on children with autism. The testing also helped establish a pressure range, because some of the subjects said it was hard to take deep breaths at the higher range. As we beginning
testing on children, we will need to avoid higher pressures, and watch the children to make sure they are breathing normally.
Chapter 6: Conclusion

6.1 Contributions

The main contributions of the research presented in this thesis are the following:

Design of a dynamic compression vest testbed that can be used to test on children with autism. Current compression vests used for sensory-based interventions are static and the effect wears off after time. The dynamic compression vest could potentially be more effective than current devices on the market. Since there is no research on dynamic compression, tests need to be performed to determine good timing and pressure parameters that would be beneficial for children. This vest allows the pressure and time components to be easily varied so it can be used to investigate these parameters.

Correlation of air pressure inside the vest and contact pressure on the user. A pressure sensor was used to determine the contact pressure on a mannequin from the vest at different bladder pressures. From this test, the contact pressure can be determined when testing the vest in the future. It is important to know the contact pressure, as this is the mechanism that the mechanoreceptors sense during sensory-based interventions.

Testing a dynamic compression vest on healthy subjects. The vest was tested on 5 healthy subjects in order to verify the safety of the vest, and to determine pressure ranges that were comfortable to healthy subjects. During the testing, there were no problems with the vest or
the code functioning properly. During the testing no subjects complained of any pain caused by the vest. These tests showed the vest is safe to be used for additional testing. These tests also helped establish pressure ranges, as at the higher pressure range, 0.3 – 0.5 psi, some subjects commented that it was difficult to take a deep breath. We will want to avoid pressures in this range when testing on children in order to make sure they are safe.

6.2 Additional Applications

This thesis presents the design of a dynamic compression vest that applies sensory-based interventions for children with autism. Additional research based on this vest could involve:

**Testing the vest on children with autism to establish comfortable pressure ranges.** In order to completely evaluate the design of the compression vest, it should be tested on children with autism. Tests can be run to see if children will wear and tolerate the vest. Feedback from this testing can be incorporated into future prototypes of the vest. This testing can also continue to establish pressure ranges that can be used with the vest, by observing children’s responses to different pressure levels.

**Investigate the effectiveness of dynamic sensory integration with varying pressure and timing parameters.** The effectiveness of the dynamic sensory-based interventions from the compression vest needs to be determined. Tests can be run on children with autism to compare the differences in behaviors between having the vest on and having the vest off. Pressure parameters can be varied during the testing to determine if different pressure levels
affect the children differently. Timing parameters can also be varied to determine if the effectiveness of the vest wears off after a certain amount of time.

### 6.3 Future Work

Future work will include continuing to reduce the weight and size of the vest components, as well as a new control system that is completely self-contained on the vest.

**Reduce size and noise of pneumatic components.** This prototype reduced the size and weight of the components from the first prototype. The components for the vest were moved from the table outside of the vest, onto a hardware box that could be kept on the vest. These components could still be improved by further reducing their size and weight. A bigger problem than the size is the noise from the pump. The noise could be from the vibrations inside the pump, or the pump vibrating against the plexiglass. This could be improved by adding insulation around the pump to reduce the noise. Another possibly way to reduce the noise would be to use a different type of pump instead of a diaphragm pump. Another type of pump, such as a vane pump, would not vibrate and could potentially decrease the noise.

**Fabricate a smaller vest that could be tested on smaller children.** The current vest and bladders were sized in order to fit adults so we could test the vest on them. Since there are Velcro straps on the vest, it will also fit on some older children, but it cannot be tested on younger children. In order to test the vest on several children, we will need different sizes. A smaller vest can be designed that could still connect to the hardware box, so the only smaller components would be the bladders and the actual vest.
**Re-design control system to fit entirely on the vest with no outside attachments.** The current control system has the ability to easily and quickly change the parameters on the vest. This will be very important as the vest is tested on multiple children to explore different pressure and timing parameters. Because of this level of control, the vest is connected from a computer through a conductor cable. While it will be adequate to have this cable during testing, before the vest can be used for extended periods of time, the control system and power source will need to be moved to the vest to make it completely self-contained.

**6.4 Summary**

The overall goal of this research is to design and commercialize a dynamic compression vest that will be more effective than vests that are currently used. Before the vest can be commercialized, there are many questions about dynamic sensory-based interventions that need to be answered. In order to answer these questions, a second prototype of a dynamic compression vest was designed with smaller components and the ability to easily change control parameters so the vest can be used as a testbed. The size of the pneumatic and electrical systems was minimized in order to fit these components on the vest, which makes the vest easier to test. The control system was redesigned with the vest controlled in LabVIEW and a user interface added to make the operation of the vest easier. Pressure transducers were added in order to use the air pressure as feedback, and tests were run to correlate this air pressure to the contact pressure applied from the vest. After the vest was designed it was tested on healthy subjects to ensure there were no problems with the vest. The testing was successful, as there were no issues, and no subjects were in pain as a
result of the vest. The vest can now be tested on children with autism to begin testing the effectiveness of children with autism, and testing different pressure and timing parameters to determine effective ranges.
References


