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DEVELOPMENT OF A PRESSURE MEASURING GARMENT TO UNDERSTAND HOW TO QUANTIFY COMPRESSION

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ABSTRACT

Encouraging research shows reductions in the number of disruptive behaviors for children diagnosed with Autism Spectrum Disorder (ASD) when wearing compression shirts. However, current studies do not consider the amount of pressure compression shirts apply to the body and how different amounts of pressure applied to the body may lead to different outcomes for children diagnosed with ASD. The purpose of this proof of concept research project was to develop a method for measuring the pressure applied by a compression shirt at a specific location on the body. This study used conductive thread as the principle element to measure the compression applied by a garment onto the body, specifically the arm. It was found that for the specific stitch and thread tested, the relationship between the displacement the sensor exhibits and the change in resistance was 25.95 Ω/m. With this relation, the pressure applied by a compression garment to a mannequin arm and the arms of four participants was found. A general trend that the measured pressure applied by a garment onto the body directly correlated with increasing individual arm circumference was found.

Keywords: compression garment, compression measurement, conductive thread, stitch sensor, pressure sensor

NOMENCLATURE

R	Resistance
L	Length
A	Cross sectional Area
ρ	Resistivity
σ	Stress
r	Radius
T	Thickness
E	Young's Modulus
ε	Strain
δ	Displacement
S.V.	State Value
V	Voltage

INTRODUCTION

According to the Psychiatric Association (2013), the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) defines Autism Spectrum Disorder (ASD) as observed impairments in social and communicative interaction, excessive non-verbal or verbal behavior, and differences in the response to sensory stimulation. Recently, integrating and responding to sensory stimuli has been identified as key characteristics of ASD [1]. Sensory-based interventions aim to increase attention and decrease stereotypical, disruptive, and self-injurious behaviors. Specific sensory interventions have been developed to address the following sensory systems: proprioceptive, tactile, visual, auditory, and vestibular. Wearable solutions and deep pressure stimulation, such as compression garments, have been identified as areas of potential research for ASD tactile interventions [2]. Deficits in tactile stimulation for people with ASD, which is measured by the tactile detection threshold, can lead to hyper/hypo sensitivity responses [3]. Furthermore, threshold sensitivity for tactile stimuli can be linked to stereotypical and disruptive behaviors and other characteristics of ASD [4]. Wearing a compression garment, such as a shirt, can increase the tactile sensory detection and thus a greater action potential input is needed to stimulate the senses. Therefore, by having subthreshold tactile input from a compression shirt the sensory threshold of an individual with ASD increases and thus someone will have decreased sensitivity to tactile input. When someone with ASD has decreased sensitivity to tactile input they are more likely to decrease the amount of stereotypical and disruptive behaviors as well as increase attention and focus [4]. Currently, therapists and families are using compression shirts as interventions despite limited research involving compression shirts for children with ASD. Furthermore, the design of the

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compression shirts used are tailored to other applications such as sports recovery.

Compression garments are also not always associated with reductions in stereotypical and disruptive behavior in children with ASD. Current studies do not measure the specific pressure a compression garment provides at different locations across the body. Similar compression garments may deliver very different amounts of pressure on a child, depending on age, body size, and shape. The amount of pressure that a child with ASD receives may be a factor involved in whether compression garments as an intervention reduces incidents of an individual's stereotypical or disruptive behaviors. However, the authors have found that the pressure supplied by compression garments used as interventions for children with ASD has not been explored in the academic literature.

This study aims to quantify the amount of pressure on the body produced by a compression shirt in order to promote future research in evaluating the effectiveness of compression garments for the reduction of disruptive behavior incidents by children with ASD. The results of this study will allow for a method for quantification of the amount of pressure provided by a compression shirt, with the idea to accurately prescribe an appropriately sized compression garment with adequate pressure to help a child with ASD.

BACKGROUND

In order to quantify the amount of pressure being applied to a person wearing a compression garment, a method for measuring the pressure at different locations had to be developed. For this experiment, conductive thread was used as the principle element and sewn into a sensor to find a correlation between pressure and an electrical response.

Using conductive thread as a method to relate different conditions of the body to an electrical signal is not a new concept. Several papers have explored the use of stitched conductive thread sensors in the use of measuring the angle of joints and motion tracking [5], [6]. However, using these stitched sensors to measure the pressure applied by a garment on the body is a novel idea. In order to accomplish pressure measurement with a stitched sensor, we need to understand how to relate displacement of the stitch to a measurable electrical response and how this can be related to the pressure being applied.

In order to relate pressure to an electrical response, the electro-mechanical properties of the conductive thread must be examined. Other papers have explored the effects of varying the thickness of the conductive thread. One study found that thicker 4-ply and 5-ply threads had higher sensitivity and accuracy than the 2-ply thread but were more limited in the movement of the stitches on the garment [7]. The reason sensitivity and accuracy were better was due to decreases in the shadow effect for the 4-ply and 5-ply samples, as discussed in [5]. However, due to the decrease in movement that the larger ply materials would provide, a 2-ply silver coated nylon conductive thread was selected to be used for this experiment. Stress and elongation of different types of stitch patterns has also been discussed extensively in [5],[7], and thus is not considered here.

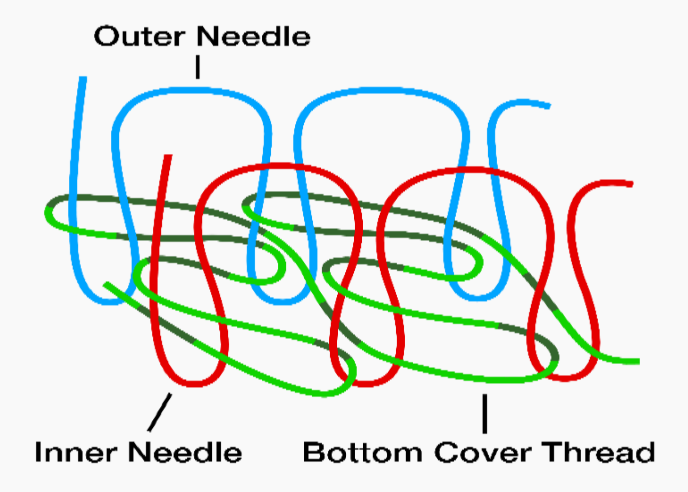


Figure 1: A diagram of what a 2-needle bottom cover stitch is.

Several studies have also explored how different stitch types affect the electrical response to the displacement of these stitches as a sensor. It has been shown from [7], that the coverstitch as seen in Figure 1, (1) has a more accurate electrical response to displacement and (2) can reach much larger displacements than other stitch types. The reason the coverstitch has such a large range is due to its geometry. As the sensor is stretched, the cross sections, as seen in Figure 1 in green on the bottom, shift across each other and elongate, therefore changing the resistance of the sensor. The reason stitched sensors change resistance is due to Equation 1 below.

$$\text{Resistance (R)} = \frac{\rho L}{A} \quad (1)$$

Where ρ is the resistivity of the material, L is the length of the thread, and A is the cross-sectional area of the thread. As the sensor is stretched the length of the sensor is changing, therefore changing the resistance. The ISO 406 standard for a 2-needle bottom coverstitch was used for each sensor on the compression shirt, where the single bottom looper thread in the sewing machine was conductive thread.

Using Equation 1, we can start to see how a sensor made from conductive thread can be used to relate a length to an electrical response. However, in order to relate this displacement to pressure, several assumptions need to be made. Firstly, if we assume a shirt sleeve is similar to that of a thin-walled pressure vessel, we can use Equation 2, the hoop stress equation, to find the stress on the sleeve.

$$\sigma = \frac{Pr}{T} \quad (2)$$

Where σ is the stress on the walls of the sleeve, P is the pressure being applied to the inside of the sleeve from the body, r is the radius of the cylindrical cross-section of the sleeve, and T is the thickness of the sleeve. In order to use the hoop stress equation, we must make two assumptions. First assume that T << r, which is true because the thickness of the sleeve is about 1 mm and the

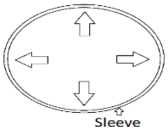


Figure 2: Sleeve with arrows indicating the direction of the pressure applied the body.

radius varies from about 2 cm to 6 cm for an average adult. Secondly, we must assume the pressure on the inside of the sleeve is applied in a radially outward direction, as shown in Figure 2. In this case, instead of having a gas or liquid provide this pressure, the body and skin of the wearer will be pushing back on the sleeve in an equal and opposite force than that of the sleeve. Due to this, Equation 2 can be used to relate stress to pressure, with the radius of the arm and the thickness of the sleeve at a specific location both known or measurable variables.

To relate the hoop stress applied to the walls of the sleeve to the resistance of the sensor, displacement must be related to stress. Equation 3, Hooke's law, can be used to relate the stress a material exhibits to the strain on the system.

$$\sigma = E\varepsilon \tag{3}$$

Where σ is the stress on the sleeve, E is the Young's Modulus, and ε is the strain on the sleeve. Strain of the system is also defined by Equation 4.

$$\varepsilon = \frac{\delta}{L} \tag{4}$$

Where ε is the strain on the sleeve, δ is the displacement the sleeve exhibits around the sleeve's circumference, and L is the starting length of the sleeve at rest. Because the sleeve has a cylindrical cross section, the length from Equation 4 is the circumference of the sleeve and the displacement is the change in this circumference. Combining Equations 2-4 and solving for pressure produces Equation 5.

$$P = \frac{E\delta T}{Lr} \tag{5}$$

Equation 5 gives us an equation relating pressure to the displacement of the sensor.

In order to measure the resistance of the stitched sensor, an AMX3D Arduino Lilypad was used to measure the voltage difference of a voltage divider circuit that was set up as shown in Figure 3 for each location on the body investigated. The Lilypad was configured to read only analog signals, as compared to digital signals, in order to read more precise measurements. Because the Lilypad is a 10-bit microcontroller, it maps the supplied voltages between 0 and 3.3V into integers between 1 and 2^{10}. This mapped value is henceforth referred to as the state value. When the Lilypad is measuring the voltage difference across the first resistor, R_1, as shown in Figure 3, it measures the voltage drop as a value between 0 and 1023, for a total of 1024 integers.

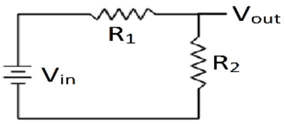


Figure 3: Voltage divider circuit.

When using a voltage divider circuit, selecting a known resistor, R_2, close to the resistance of the stitched sensor is critical. An estimate for the resistance of the stitched sensor can be calculated based on thread length since the 2-ply conductive thread used had a specified resistance close to 50Ω/m. The length of the stitched sensor allows us to estimate the resistance of the sensor and what known resistor, R_2, to use. 18Ω or 120Ω resistors were used during testing depending on the trial. From the state value, we can solve for the resistance of the sensor, R_1, from Equation 6 below.

$$R_1 = R_2\left(\frac{V_{in}}{V_{in}\frac{S.V.}{1024}} - 1\right) \tag{6}$$

Where V_{in} is the input voltage, in this case 3.3V, and R_2 is the resistance of the known resistor, and S.V. is the state value measured by the Lilypad.

The final piece of information needed was a relationship between the resistance of the stitched sensor and the length of the stitched sensor displaced. In order to find this relationship, the sensor was stretched at a known rate of displacement and the corresponding state value was measured from the Lilypad's voltage divider circuit. The slope of the linear fit line relating measured state value to measured displacement was used to convert between resistance and displacement. Ultimately this relationship between resistances and displacement was combined with Equations 5 and 6 to measure pressure at the specific location on the body the stitched sensor encircled.

METHODS

There are three separate procedures that were done for this study: (1) measuring a relationship between the displacement and the resistance of the stitched sensor, (2) construction of a single sleeve for testing with a mannequin's arm to ensure that the measurement of different pressure values at different arm circumferences differed and that similar pressure values were measured across different trials for the same arm circumference, and (3) testing of two different compression shirts on four participants to see how pressure varied across different sized individuals.

Materials

Two Arduino Lilypads and one Arduino Zero were used to measure the state values of the conductive thread via the analog ports. 2-ply silver coated nylon thread was used and was sewn into place using a Brother 2340cv coverstitch machine. The sleeve and compression shirt were an 87% Polyester and 13% Spandex blend from a commercially available Champion® brand compression shirt. Finally, an 18Ω resistor was used for the first procedure and six 120Ω resistors were used for the final two procedures, three for each Lilypad and one for each stitched sensor circuit. A stitched sensor circuit was sewn at the wrist, elbow, and bicep.

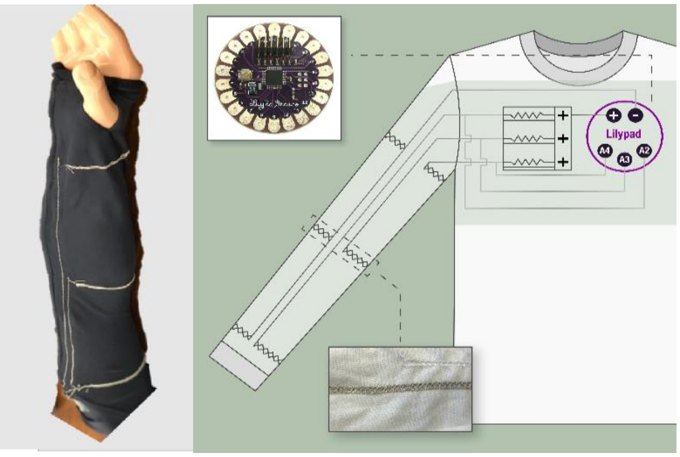
The ASTM E111-17 was followed to measure and calculate Young's modulus of the sleeve and shirt textile. A plain sample of the fabric, with the same dimensions as stated above was used to measure the Young's Modulus of the textile with the rate of displacement set to 5 cm/min for a total of two minutes. A sample was stretched a total of 10 cm over the course of two minutes. From the results of the stress-strain curve, the Young's Modulus was calculated as 0.2046 MPa.

Resistance to Displacement Relationship

A 10.2 cm by 17.8 cm section of the fabric, cut out of a compression shirt, was tested with a 7.6 cm length of conductive thread sewn into the middle of the sample parallel to the longer direction. The length of the stitched sensor was in the same direction of stretch across the body for when the fabric was stretched in the tensile testing machine. It was then placed into an MTS tensile testing machine with model number 39-075-103 and secured in place using 25 mm high and 50 mm wide grips and held in place at 241 kPa, which was applied using a torque wrench. A MTS Load Frame with a 500 N load cell operated by a hydraulic power unit, with model number 505.11 was used. The ends of the conductive thread in the stitched sensor were then connected into a voltage divider circuit, with an Arduino Zero measuring the state value of the conductive thread. The material was stretched at a rate of 3 cm/min for a total of one minute and the displacement, force, and state value of the voltage divider circuit were measured. This was done for a total of 2 different specimens, each one having the same coverstitch settings. For each specimen a relationship between the change in displacement and the change in state value of the circuit was gathered and an average was calculated.

Mannequin Trials

A mannequin arm used for venipuncture practice was procured from the College of St. Scholastica Occupational Therapy department. A sleeve with three different locations, wrist, elbow, and upper bicep, was constructed. For each of these locations a coverstitch was sewn around the circumference of the sleeve henceforth referred to as bands. Each band was also attached to two straight stitches tied into the Lilypad using the same conductive thread, one to ground and the other to the analog port. Figure 4 shows how the circuit was set up on the shirt. Once connected to the Lilypad, a resting baseline for the state value was measured for each band over the course of one minute. For this, the shirt was placed on a smooth surface and laid flat. Once the baseline state value data was gathered, the sleeve was placed on the mannequin arm and the circumference of the arm at each of the bands was measured. Once the sleeve was placed on the arm, one minute of state value data was gathered and the average pressure was calculated for each band using Equation 5 and the relationship calculated between electrical resistance and displacement. Each measurement was taken three times and averaged.



(a) (b)

Figure 4: (a) Sleeve on mannequin arm and (b) circuit setup for one of the sleeves of the shirt.

Participant Trials

For the final procedure, the medium-sized sleeve from the mannequin trial and an extra-small sized sleeve that was constructed using the same method as the first, was worn by four different participants. Two participants wore the medium size sleeve and the other two participants wore the extra small sleeve. Just like the mannequin trial, the baseline values for each sleeve were measured for a total of one minute. Once the baseline state values were gathered, a participant would wear the sleeve for one minute for three separate trials that were averaged.

RESULTS

The resistance to displacement results are discussed first. The mannequin and participant trials are discussed second.

Resistance to Displacement Relationship

Figure 5 shows the measured resistance of a stitched sensor

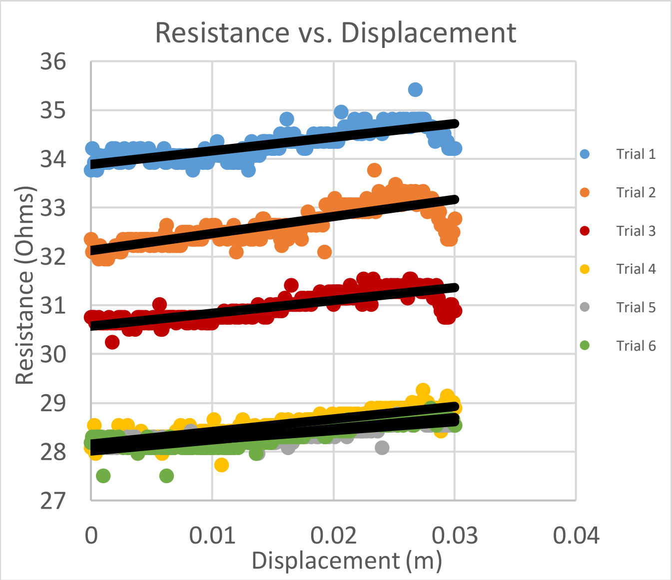


Figure 5: The change in the resistance as a function of displacement for six of the twelve trials ran.

Table 1: The slope and y-intercept for Figure 5's lines of best fit.

Trial #	Slopes (Ω/m)	y-Intercept (Ω)	R^2 Value
1	27.86	33.89	0.663
2	34.88	32.12	0.671
3	26.31	30.57	0.686
4	25.75	28.16	0.788
5	22.79	28.07	0.743
6	18.15	28.01	0.705
Average	25.95±5.55	30.13±2.48	0.701

fabric sample versus its displacement for six different trials. The black lines represent linear lines of best fit. In Table 1, the slopes and y-intercepts for the linear lines of best fit are shown, along with the average value. Note that throughout this paper the values after the "±" symbol denote the standard deviation. From Figure 5, the average linear slope between resistance and displacement for the six trials was found to be 25.95±5.55 Ω/m and an average R^2 value of 0.701. Note that the y-intercept location for all the trials are slightly different due to the fatigue of the fabric, which decreased the resting resistance or state value baseline from stretching over multiple trials in succession. Using the measured relationship between resistance and displacement shown in Figure 5 coupled with Equation 5 we can find the pressure applied at the location of the stitched sensor around the sleeve. Note more than six trials were run but due to inconsistent loading conditions of the samples, which are discussed in the discussion section, these trials are not comparable and thus not included in the Figure 5.

Mannequin and Participant Trials

For the mannequin trial, the circumference at wrist, elbow, and upper bicep are shown in Table 2, along with the same measurements for each of the participant trials. Each of these measurements were gathered once using a flexible tape measure. Note that the right arm was used for each of these trials.

Table 2: Circumferences at the wrist, elbow, and upper bicep for the mannequin and each of the four participants.

Participant (Part.)	Wrist Circum. (cm)	Elbow Circum. (cm)	Bicep Circum. (cm)	Size
1	13.9	22.8	24.7	XS
2	15.2	22.8	26.7	XS
3	15.9	25.4	30.5	M
4	15.9	28.2	36.2	M
MA	17.5	27	32.8	M

Table 3: Average pressure for each location for each participant.

Part.	Avg. pressure at wrist (mmHg)	Avg. pressure at elbow (mmHg)	Avg. pressure at bicep (mmHg)	Size
1	6.08±0.809	12.27±0.595	2.65±0.338	XS
2	19.55±0.928	4.84±2.96	6.33±3.66	XS
3	14.39±2.75	86.39±5.56	171.93±46.4	M
4	28.03±16.84	5.57±2.27	5.42±3.23	M
MA	3.89±0.77	41.99±0.024	33.58±0.030	M

Finally, in Table 3 the average pressure for each arm location for each of the participants is shown. Note that each of the pressure values are the averages found across three trials. Also, each pressure measurement was converted to mmHg because other compression garments use this unit.

DISCUSSION

For the discussion section, the results of the resistance to displacement relationship is discussed. Then the results from the mannequin and participants trials are discussed. With each of these, any major findings and errors are discussed.

Resistance to Displacement Relationship

The relationship between resistance and displacement was found to be 25.95±5.55 Ω/m. The standard deviation was small with regards to the average, meaning there is little deviation across trials. Even though the relationship between the resistance and the displacement was constant across trials, the y-intercept in Figure 5 had a large amount of variability. The variability in y-intercept is likely due to the fabric starting to fatigue after each of the trials. This means that while the base fabric is being fatigued or stretched out, the stitch will also experience some fatigue. This could cause the base resistance to drift. For the last three trials, after adjusting the distance between the grips to be slightly farther apart to counteract the fatigue of the fabric while testing, the y-intercept values were quite similar e.g. 28.16, 28.07, and 28.01 Ω. After the grips were adjusted the y-intercept did not change nearly as much in the last three trials as in the first three trials. Thus, each time the shirt was tested on the mannequin or participants, a baseline value was found by placing the shirt on a smooth solid surface and this value was used for the y-intercept to find the displacement of the stitched sensor.

Mannequin and Participant Trials

For the second part of this experiment, the repeatability of this method was tested. Over the course of three trials, the standard deviation with respect to the average for the wrist, elbow, and upper bicep was 19.7%, 0.057%, and 0.089% respectfully. The elbow and upper bicep show superior repeatability based on these standard deviation values. In contrast, the standard deviation for the wrist was significantly higher. The reason for this was the medium shirt that was used on the mannequin arm was visibly loose at the mannequin's wrist. Therefore, since the sensor was not in uniform contact with the mannequin's skin, the sensor nor the mannequin's skin would be exposed to a uniform pressure resulting in higher measurement variability.

As for the participant experiment, when comparing the differences in circumference of a participant's arm and the pressure measured, the general trend was the larger the circumference of the arm the greater the pressure. This relationship is seen in Table 2 and 3, for the wrist and upper bicep measurements between participants 1 and 2. This finding of increased pressure from the same size of garment on participants with larger arm circumference measurements at the wrist, elbow, and upper bicep locations intuitively makes sense.

However, there are three inconsistencies that can be seen from Tables 2 and 3. Firstly, the elbow and bicep measurements of participant 3 were larger than that of any of the other participants (including the mannequin), yet the pressure was unusually high at one to two orders of magnitude larger than all other participants. The possible reason for this jump in pressure measurement could be due to unintentional connection of one circuit to that of another circuit, essentially combining resistance. Also, the resting baseline value gathered for that measurement may be incorrect due to the unintentional connection of multiple circuits. Secondly, the elbow location tends to have a large variability in the measurement of pressure. The possible reason for this variability could be due to how the geometry of the arm changes quite rapidly, possibly leading to uneven pressure application to the sensor. Inconsistency in how the elbow circumference was measured could also contribute to this variability. Finally, for the mannequin arm, the elbow and upper bicep pressure measurements were quite large compared to the participant measurements. The possible reason for this could be due to the mannequin arm being a rigid structure with little give, whereas the human body will have some give when compressed.

There were three sources of error to this experiment that could be improved upon in future work. Firstly, a large load frame was used to stretch the fabric sample during testing. However, the hydraulic power unit operating the load frame's movement created vibrations that can create an error of ±5 Newtons. This lack of precision leads to some inherent error for the displacement and resistance relationship measured. Secondly, there was no place near the grips of the load frame to place and connect to an Arduino Zero. Thus, two large leads were used to connect the stitched sensor to the microcontroller. Combining all of this together, the results for the resistance-displacement relationship should be run again with a smaller tensile testing apparatus that is designed for fabrics. Finally, unintentional grounding was another source of error. When the shirts were tested on the mannequin and the participants, six different leads were running up the sleeve and five more leads were on the shirt to connect the Lilypad to the breadboard. When two of these circuits come in contact with each other a higher resistance is measured resulting in inaccurately high pressure.

For future experiments, an exploration of using different types of conductive thread and stitch patterns needs to be explored to establish a better relationship between displacement and resistance. Also, using a larger bit microcontroller will also increase the accuracy of the data gathered. Finally, based on our findings, we can design a compression garment with specific pressure to better explore the effects that compression has for children with ASD.

CONCLUSIONS

Three main conclusions come from this research. This experiment established an average slope between resistance and displacement for a stitched sensor made with 2-ply silver coated nylon thread and 2-needle bottom coverstitch of 25.95±5.55 Ω/m. Secondly, measuring pressure with a stitched sensor embedded garment is consistent for measuring pressure in wrist and upper bicep arm locations across trials with the same participant. Finally, this method for determining pressure has shown the potential to distinguish the difference between arms of different circumferences. Future work measuring pressure at these arm locations needs to be done in order to confirm that the calculated pressure values are accurate.

ACKNOWLEDGEMENTS

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