A Large-Area Wearable Soft Haptic Device Using Stacked Pneumatic Pouch Actuation

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Abstract— **While haptics research has traditionally focused on the fingertips and hands, other locations on the body provide large areas of skin that could be utilized to relay large-area haptic sensations. Researchers have thus developed wearable devices that use distributed vibrotactile actuators and distributed pneumatic force displays, but these methods have limitations. In prior work, we presented a novel actuation technique involving stacking pneumatic pouches and evaluated the actuator output. In this work, we developed a wearable haptic device using this actuation technique and evaluated how the actuator output is perceived. We conducted a user study with 20 participants to evaluate users' perception thresholds, ability to localize, and ability to detect differences in contact area and compare their perception using the stacked pneumatic pouch actuation to traditional single-layer pouch actuation. We also used our device with stacked pneumatic actuation in a demonstration of a haptic hug that replicates the dynamics, pressure profile, and mapping to the human back, showcasing how this actuation technique can be used to create novel haptic stimuli.**

I. Introduction

Human haptic perception research and haptic device development has focused on the fingertips and hands due to their high mechanoreceptor density. However, other locations on the body can play a key role in conveying and interpreting haptic sensations. For example, the chest, back, and arms are important in many social haptic interactions. These areas offer large skin "real estate" compared to the small surface area of the fingertips and hands, but the haptic perception is less understood. In order to effectively exploit these large areas of skin to convey rich and complex haptic information, we aim to further explore haptic perception at these areas.

Most prior work in large-area body-grounded haptic devices has focused on providing vibrotactile feedback via distributed actuators. However, vibration alone is limited in the complexity of sensations that it can provide and cannot realistically mimic human touch. Pneumatic force displays are capable of producing skin compression as well as vibrotactile sensations in a lightweight, conformable form factor. Prior work has embedded pneumatic pouch actuation in vests [1], jackets [2], [3], and other form factors [4]. Pouch-based pneumatic force displays like these are typically singular or distributed pouches controlled through closed-loop feedback, either measuring pouch internal air pressure or external contact force or pressure. However, as highlighted in [5], pouches with low pressure and large contact area can produce the same magnitude of force as pouches with high pressure and small contact area, but the physical sensations would not be the same. Understanding the perception of these different sensations and being able to independently control both contact area and applied pressure would allow the creation of more sophisticated haptic sensations.

The properties of pouch actuators, such as their dynamics and their contact area with surrounding surfaces, can be changed by altering their configuration as shown in [6]. Pouches can be arranged so that smaller pouches, proximal to the skin, are stacked atop larger pouches located more distally. Our prior work has demonstrated the utility of a stacked pouch actuation scheme, analogous to macro-mini actuation in robotic manipulators [7], to enable control of the contact area independent of pressure and increase the speed of dynamic response as compared to single pouches [5].

In this paper, we actualize macro-mini pouch actuation in a wearable large-area soft haptic device. Previously we showed how stacked pouch actuators affected *applied* pressure and *physically* altered contact area [5]. Now, with a wearable device, we investigate how stacking affects *perceived* pressure by conducting a study to calculate detection thresholds and *perceived* contact area by conducting a localization study. We describe the device design in Section II. Section III presents user studies investigating human haptic perception of the macro-mini actuation approach compared to a single layer of pneumatic pouches. In Section IV we demonstrate that our device can replicate the varying pressure distributions occurring during a hug. We summarize our findings and describe future work in Section V.

II. Device Designs

This section describes the design of two wearable devices, one with stacked macro-mini pouches and one with single-layer pouches for comparison, that apply haptic feedback to the human back using soft pneumatic actuators. We discuss the hardware elements of the devices, including the design and fabrication of the pneumatic actuators, construction of the wearable housing, and configuration of the actuator arrays. Then, we describe the system architecture and control

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of the devices. Because the equipment used to build and control the devices were designed and rated using US Customary Units, we will report the equivalent measurements using the International System of Units for initial definitions and will use US Customary Units thereafter.

A. Hardware

1) Pneumatic Actuators: The pneumatic pouch actuators are thin sheets formed into pouches that apply pressure as they inflate. In general, these actuators can be fabricated from any airtight, flexible, inextensible material. We fabricated pouch actuators from low-density polyethylene (LDPE) tubes with a $2.99 * 10^{-3}$ inch (76 μm) wall thickness, due to low cost and ease of fabrication. The pouch edges were heat sealed using an impulse sealer, and a 1/4-inch (6.35 mm) straight push-to-connect through-wall connector (McMaster-Carr) allowed air flow to each pouch.

These actuators can be arranged in parallel (next to one another) and in series (stacked on top of one another). Stacking enables an extra degree of freedom by allowing a change in contact area, as well as increasing the inflation height and speed of the combined system [5]. In addition, not all pouches need to be of identical size, and pouches that inflate together can be combined into equivalent single larger pouches. We refer to stacked configurations, especially those with large and small pouches, as "macro-mini" actuation [7].

2) Wearable Housing: The wearable housing used extra large mesh worker's vests (Everyday Mesh Vests, PeerBasics) as the base. These are thin and lightweight, draping over the user's shoulders and securing via velcro on the front of the vest. The housing rigidity was increased with a layer of 12 oz (340 g) canvas drop cloth (SuperTuff Canvas Drop Cloth, Trimaco). In our user study (Section III), we found that these vests could be worn by all participants.

3) Array Configuration: The final component of the haptic display design was the actuator arrangement within the wearable housing. Our goal was to build a device that could compress the skin over large areas on the back so that we could evaluate human perception pertaining to pressure and perceived contact area at different locations. We tested many array configurations during prototyping and initial pilot testing, varying pouch number, size, and spacing. From our initial tests, we found that the contact area varies more with larger pouches. However, using few large pouches limited the number of contact locations that we could test. We decided on the finalized array configurations shown in Fig. 1 as it allowed us conduct this initial study of human perception of large area force application as well as perception of different contact areas. The single-layer pouch vest includes 14 parallel pouch actuators, all 4 inches (10.2 cm) square. The macro-mini pouch vest includes the same 14 parallel pouch actuators stacked atop a set of 12 larger pouch actuators. The layer of smaller pouches (mini) is responsible for delivering the soft haptic stimulation while the layer of larger pouches (macro) inflates to conform the device to the body and ensure physical contact between pouches and user. The 16-inch (40.6 cm) long pouch actuators (pouches 22 and 25 in Fig. 1) adapt the wearable device to the lower back's curvature when inflated. The 4-inch (10.2 cm) by 5-inch (12.7 cm) pouch actuators on each side wrap the device around the user.

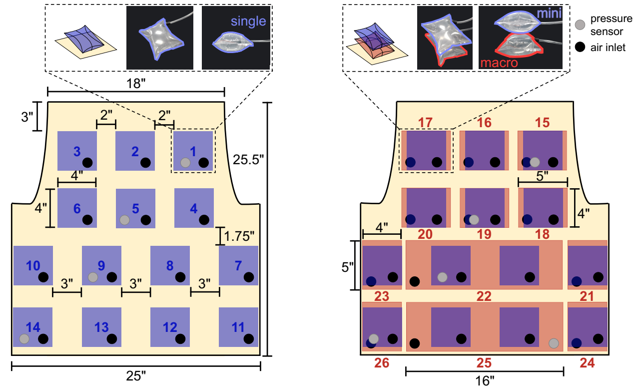

Fig. 1. Final designs and layout of the pneumatic pouches for the single layer pouch vest (left) and macro-mini pouch vest (right).

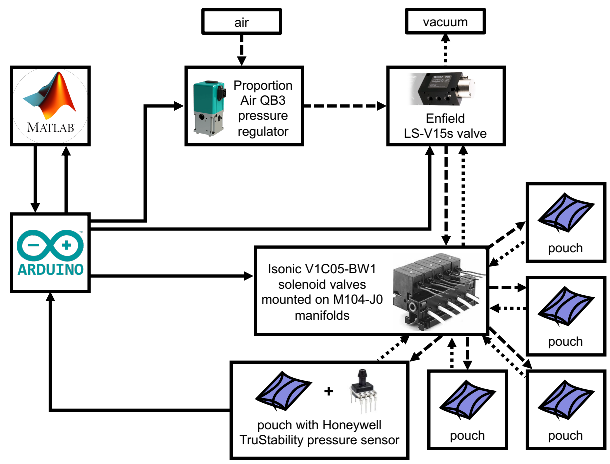

Fig. 2. Pneumatic system for controlling the pressure to individual pouches on the vest. For simplicity in the schematic, we show only 5 pouches which can be large or small. Solid lines indicate the flow of electrical signals, dashed lines indicate air flow, and dotted lines indicate the flow of vacuum.

B. System Architecture

The inflation of the pouches is controlled by the pneumatic system shown in Fig. 2. Each pouch actuator is connected to the control system using 6 feet (1.83 m) of 1/4-inch (6.35 mm) outer diameter tubing and 1 foot (0.305 m) of 5/32-inch (3.97 mm) outer diameter tubing. The tubing was specifically measured to ensure equal fluidic resistance for each pouch. The tubing connects to Isonic V1C05-BW1 3/2-way solenoid valves mounted on M104-J0 manifolds (Mead Fluid Dynamics), which switch the flow on or off to each pouch. These manifolds connect to an LS-V15s 5/3-way proportional directional valve (Enfield Technologies) which controls whether the current flow from the manifolds should be inflation (receive commanded pressure) or deflation (connected to vacuum). The command pressure is controlled by a Proportion Air QB3 pressure regulator.

Pressure was measured by sensors (Honeywell TruStability® Board Mount Pressure Sensors SSC Series 030PAAA5) integrated into actuators on each vest: four in the 4-inch pouch actuators in a diagonal pattern (numbers 1, 5, 9, and 14), and one in the 16-inch macro pouch actuator on the bottom row of the macro-mini pouch vest (Fig. 1). While in the future these sensors could be used for closed-loop control of pouch inflation, here they are used to confirm successful inflation to the desired pressure while the devices are worn.

The pneumatic system was controlled using a microcontroller board (Arduino Mega 2560). Digital signals sent from the Arduino to ULN2803 Darlington arrays open and close the 3/2-way solenoid valves. A PWM signal switches the Enfield LS15s valve between no airflow, airflow, and vacuum. Finally, a PWM signal is sent to the QB3 pressure regulator to command a specific output pressure. We also use the Arduino analog input pins to collect pressure sensor data. All commands are communicated serially to the Arduino from a computer. We use a MATLAB Support Package for Arduino to integrate our control system with a graphical user interface (GUI) for data collection and human subjects studies.

III. User Study

To evaluate human perception of the applied stimuli, we performed a two-part human-subject study using the single layer and macro-mini pouch vests in Section II. The first part investigated the detection threshold (minimum control pressure needed to detect a stimuli) at four locations and the second part assessed participants' ability to localize the haptic stimuli.

A. Hypotheses

Based on the experiments conducted in [5], we hypothesized that the macro-mini pouch device would result in lower detection thresholds as compared to the single-layer pouch device and that the perceived contact area of the haptic feedback would be larger with the macro-mini pouch device than the single-layer pouch device and that the perceived contact area would increase with control pressure. Finally, we hypothesized that participants would prefer the macro-mini pouch device to the single-layer pouch device because of the more distinguishable haptic feedback.

B. Participants

Twenty-one participants (10 female, 11 male) with an age range of 20-33 years (mean and standard deviation of 25.9 ± 4.0 years) consented to participate in the study, which was approved by the Stanford University Institutional Review Board. None of the participants had neurological disorders or any other conditions that would have affected their performance in this experiment. Seven participants reported that they were very familiar with haptics, nine reported that they had some familiarity with haptics, and five reported being unfamiliar with haptics prior to participating in the study.

C. Procedure

After reading and signing the consent form, participants changed into a clean, unisex t-shirt (60% cotton, 40% polyester blend) to ensure all participants had the same base clothing layer to minimize the impact of clothing choice on perception of the haptic devices. They could choose a shirt size from extra small to extra large. Participants wore two novel soft wearable haptic devices and provided responses about what they felt. They completed the two-part study for one device, took a 5-minute break, and then completed the two-part study for the second device. After completing the studies for both devices, partipants completed a short survey.

The order of the two devices was randomly determined for each participant, and the order was balanced across all participants. After donning a device with the help of the experimenter, participants followed instructions provided by a GUI on the computer monitor (Fig. 3). Participants wore Bose QuietComfort 25 noise cancelling headphones playing white noise to prevent auditory distractions or cues.

Participants pressed the "start" button to begin each study section, signaling the device to "fit" to their upper body. For both devices, the GUI informed participants that the device was being fit and instructed them to wait before continuing (90 seconds for macro-mini pouch device and 10 seconds for single-layer pouch device). During this waiting time, pouches 13-26 in the macro-mini pouch device were inflated to 1.0 psi (6.89 kPa) and nothing changed in the single-layer pouch device. Once the device was "fit" to the user, participants were prompted by the GUI to press "start" to begin this part of the study.

For the threshold detection experiment, participants pressed "start" on the GUI, triggering the first signal to be sent to the actuators in the device. They were then prompted on the screen to state whether they felt a haptic sensation applied to their back, choosing either "yes" or "no". The next trial began immediately after they responded. Participants continued responding to signals by following the prompts from the GUI. In this part, there were four sections that correspond to different pouch locations – specifically pouches 1, 5, 9, or 14 (Fig. 1). We chose these pouch locations to examine if and how stimuli perception changes from varying the vertical or horizontal position on the human back. The GUI informed the participants when they had completed each section and that they could take a one-minute break between sections. The order of the pouch locations was randomly determined for each participant, and balanced across all participants.

Fig. 3. Experimental setup showing a participant wearing one of the soft haptic vests and interacting with the graphical user interface. Participants could not see the haptic stimuli applied to their back and wore noise-cancelling headphones playing white noise to mask any auditory cues.

For each threshold detection trial, the following occurred: (1) a pressure value was sent to the QB3 pressure regulator, (2) the individual pouch 3/2-way solenoid valve was set to open, (3) the 5/3-way proportional directional air control valve was set to allow airflow for 5 seconds, (4) the 5/3-way proportional directional air control valve was switched to vacuum for 2 seconds, and (5) the individual pouch 3/2-way solenoid valve was closed. The commanded pressure for the first trial in each section was 0 psi/kPa. The command pressure for each following trial was determined following a simple up-down staircase method [8] using the participants response as to whether or not they felt the stimuli. If the participant stated that they did not feel a sensation, then the command pressure for the next trial increased by 0.05 psi (0.345 kPa). Alternatively, if the participant stated that they felt a sensation, the command pressure for the next trial decreased by 0.05 psi. The minimum commanded pressure was 0 psi; if the participant stated that they felt a sensation at a command pressure of 0 psi, then the command pressure for the subsequent trial was also 0 psi.

We recorded each instance that a participant's response differed from their previous response (a reversal). The participants completed the section after 8 reversals. The participants also completed the section after they completed 40 successive trials without recording a reversal; for example, 40 successive "yes" responses (repeated commanded pressures of 0 psi) or 40 successive "no" responses (final commanded pressure of 2.0 psi (13.8 kPa)). On average, participants completed all four sections of the threshold experiment in 30 minutes.

For the localization experiment, participants similarly pressed "start" to trigger the first signal to be sent to the actuators in the device. They would then select where they felt the sensation on a silhouette on the screen (Fig. 3). By clicking and dragging a circular region on screen, participants selected the size and location of the circle to match the location and contact area of the sensation that they felt. If they did not feel a sensation, they created a circle over the question mark located in the upper right hand of the figure window. Once they were finished adjusting the circle, they submitted their response and continued to the next trial.

For each trial, we used the same 5-step actuation as described for the threshold experiment. We varied the commanded pressure (0.3, 0.5, and 1.0 psi – 2.07, 3.45, and 6.89 kPa, respectively) and the pouch location (pouches 1-14) for each trial. This resulted in 42 unique actuation conditions. The order of conditions was randomized for each participant. The participants completed the localization experiment in an average of 15 minutes.

After participants completed testing with both devices, they completed a short survey which included demographic questions (age, gender, and previous experience with haptics) and questions about their experiences with the two devices, including whether they preferred the first or second device, and comments they had regarding each of the devices, what differences, if any, they noticed between the devices, and any additional comments. Finally, the experimenter recorded measurements of their bust, waist, hip, and torso.

D. Results

During the study, there was a minor device malfunction for one participant. We conducted all of our analyses with the remaining 20 participants.

1) Detection Threshold Experiment: We calculated the detection threshold for each participant at each location for both devices. To do this, we first identified the reversals in the staircase. Then, we calculated the transition points by averaging the values of the reversal points and the values prior to the reversals. We then averaged the transition points to determine the detection threshold [8].

If a participant did not provide any responses that resulted in a reversal, then we recorded the detection threshold as 2.0 psi, which was the final commanded pressure (9 out of 160 trials). We acknowledge that this is not the participants' true detection threshold, which would actually be higher than 2.0 psi. Similarly, if a participant provided less than 8 reversals, we recorded the detection threshold as 0 psi (27 out of 160 trials). Again, we acknowledge that the participants' detection threshold is not truly 0 psi. An exact calculation of detection thresholds for such participants would require increased pressure control resolution and range.

Figure 4 shows boxplots of the participants' detection thresholds for each device at all of the pouch locations. The Wilcoxon signed-rank test, the non-parametric equivalent to the paired t-test, is used to compare two sets of data that come from the same participants and are not normally distributed. The independent variable in these analyses was device and the dependent variable was detection threshold. The Wilcoxon signed-rank tests showed that there was a significant difference in detection thresholds for pouches 5 ($p = 0.014$) and 9 ($p = 0.022$), but not for pouches 1 or 14.

2) Localization Experiment: Figure 5 shows heatmaps of the participants' submitted circle objects pertaining to pouch 4 for each device at each commanded pressure level. This is an example for one pouch to facilitate visualizing and interpreting the presented results and statistical analysis. The

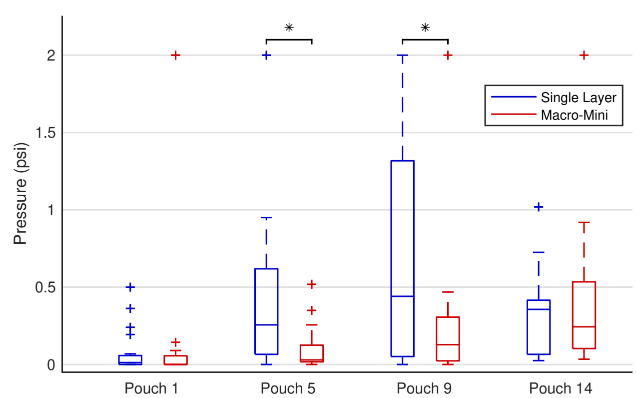

Fig. 4. Boxplots of detection thresholds. The central line in each box indicates the median, and the bottom and top edges of the boxes indicate the 25th and 75th percentiles, respectively. Outliers are marked with the '+' symbol. Statistical significance from the Wilcoxon signed-rank tests are indicated by $*: p < 0.05$.

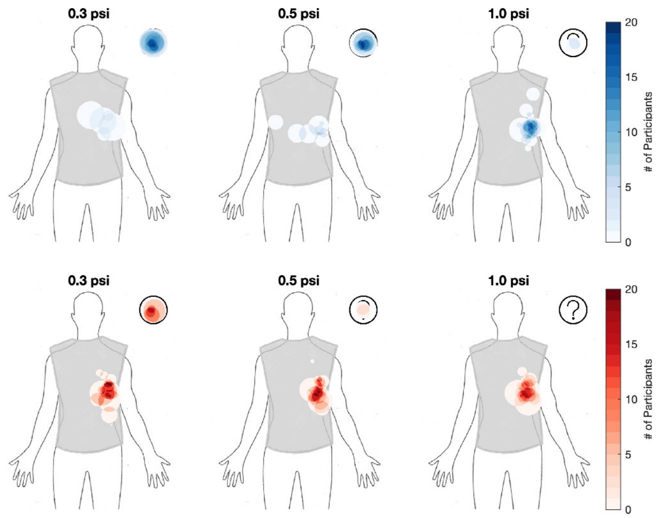

Fig. 5. Heatmaps of participants' submitted circle objects for pouch 4. The axes in the colorbar correspond to the number of participants. Responses for the single-layer pouch device (top) and macro-mini pouch device (bottom) are shown separated by commanded pressure.

top plot in Fig. 5 shows the results for the single-layer pouch device. For a command pressure of 0.3 psi, there is a high density of responses on the question mark, indicating that participants had difficulty feeling and localizing the sensation. As the command pressure increased, fewer participants reported that they could not feel the sensation and a higher density of responses around the approximate location of pouch 4 (Fig. 1). In comparison, the bottom plot in Fig. 5 shows the results for the macro-mini pouch device. Even at 0.3 psi, there is a high density of responses near the approximate location of pouch 4 on the vest. Fewer participants reported that they could not feel the sensations, and every participant was able to localize the sensation at 1.0 psi command pressure. The heatmaps for other pouch locations show these same trends (at varying levels).

We counted the total number of trials participants who reported that they did not feel a sensation (Table I). We then calculated the mean center of the reported circle objects at each combination of device type, pressure, and pouch location. Instances when participants did not feel a sensation were excluded when calculating center positions. We then computed the distance of each participant's response with respect to this mean center for the given combination of conditions from the calculated mean. Figure 6 reports the mean and standard deviation of the distances for each commanded pressure at each pouch location separated by device.

We ran a four-way ANOVA on the computed distance from the mean center with device type, pouch location, commanded pressure, and subject (to take individual participant variability into account in our model) as factors. The interactions between device and pouch location ($F(13,1679) = 14.87$, $p < .001$), device and pressure ($F(2,1679) = 4.42$, $p = .012$), device and subject ($F(19,1679) = 3.24$, $p < .001$), pouch and pressure ($F(26,1679) = 3.55$, $p < .001$), pouch and subject ($F(247,1679) = 2.15$, $p < .001$), and pressure and subject ($F(38,1679) = 1.78$, $p = .003$) were all

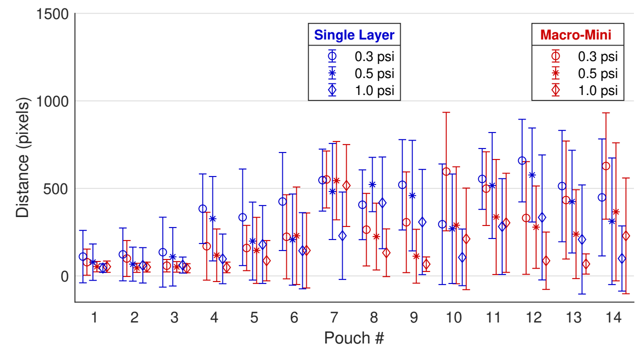

Fig. 6. Mean and standard deviation of the distance of the circle object provided by the participants from the calculated mean center during each trial in part two of the user study separated by device, pouch location, and commanded pressure.

significant. The ANOVA showed that the distance from the mean center for the macro-mini pouch vest was significantly smaller than the single-layer pouch vest ($F(1,1679) = 58.43$, $p < .001$) and was confirmed via a post-hoc pairwise comparison test with a Bonferroni correction ($p < .001$). The ANOVA also showed that there was a significant difference in the distance from the mean center across pouch location ($F(13,1679) = 51.49$, $p < .001$). Again, we conducted a post-hoc pairwise comparison test with a Bonferroni correction to determine which pouches were significantly different from one another. The statistical significance for this post-hoc test can be found in Fig. 7(a). This ANOVA also showed that there was a significant difference in the distance from the mean for each commanded pressure ($F(2,1679) = 125.66$, $p < .001$) and post-hoc pairwise comparison test with a Bonferroni correction confirmed that the computed distances from the mean center for 0.5 psi were significantly smaller than 0.3 psi ($p < .001$) and 1.0 psi ($p < .001$) were significantly smaller than 0.5 psi, indicating that increased pressure resulted in more localized clustering of participant responses. As anticipated, the ANOVA showed that subject was a significant factor ($F(19,1679) = 10.81$, $p < .001$).

Next, we ran multiple Pearson's Chi-square test for independence to compare the number of times participants did not feel any sensation to the number of times that they did feel a sensation using the contingency tables shown in Table I. The Chi-square result for device is $\chi^2(1, N = 1680) = 38.25$, $p < .001$, indicating that there is a significant effect of the device on the number of times that participants did not feel a sensation. Similarly, the Chi-square result for pressure ($\chi^2(2, N = 1680) = 113.00$, $p < .001$) indicates that there is significant effect of pressure on number of times that participants did not feel a sensation. Finally, the result for pouch number ($\chi^2(13, N = 1680) = 264.94$, $p < .001$) indicates there is a significant effect of the pouch location on the number of times that participants did not feel a sensation.

Figure 8 reports the mean and standard deviation of the radii of the circle object that participants provided for each commanded pressure at each pouch location.

Before conducting our statistical analyses, we standardized (calculated the z-score) the radii data. We then ran a three-way ANOVA on the radii with device type, pouch loca-

		Device		
		Single Layer	Macro-Mini	Totals
Felt sensation?	No	317	200	517
	Yes	523	640	1163
	Totals	840	840	1680

		Pressure			
		0.3 psi	0.5 psi	1.0 psi	Totals
Felt sensation?	No	252	177	88	517
	Yes	308	383	472	1163
	Totals	560	560	560	1680

		Pouch														
		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	Totals
Felt sensation?	No	4	5	5	35	24	35	84	51	39	36	65	52	39	43	517
	Yes	116	115	115	85	96	85	36	69	81	84	55	68	81	77	1163
	Totals	120	120	120	120	120	120	120	120	120	120	120	120	120	120	1680

TABLE I

CONTINGENCY TABLES: COUNTS OF THE TOTAL NUMBER OF TRIALS PARTICIPANTS DID NOT FEEL A SENSATION SEPARATED BY FACTOR

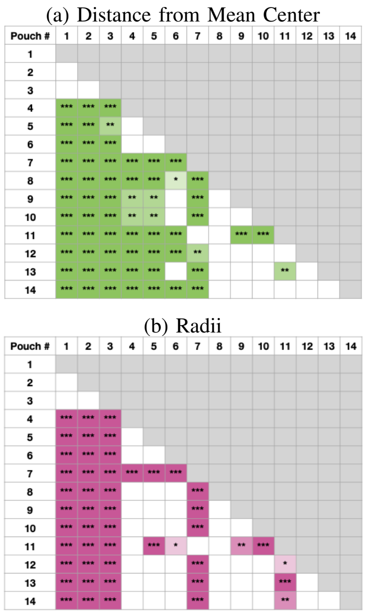

Fig. 7. Results of post-hoc pairwise comparison tests with a Bonferroni correction for pouch location. Standard significance notation is used ($*: 0.01 < p < 0.05$, $**: 0.001 < p < 0.01$, $***: p < 0.001$).

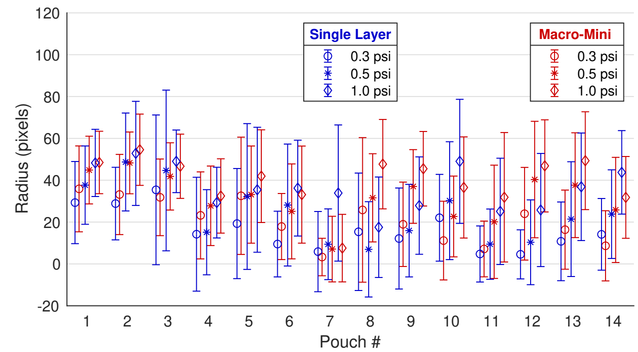

Fig. 8. Mean and standard deviation of the radii of the circle object provided by the participants during each trial in part two of the user study separated by device, pouch location, and commanded pressure.

tion, and commanded pressure as factors. The interactions between device and pouch location ($F(13,1679) = 10.05$, $p < .001$) and device and pressure ($F(2,1679) = 4.00$, $p = .019$) were significant, while the interaction between pouch location and pressure ($F(26,1679) = 1.24$, $p = .188$) was not. This ANOVA showed that reported radii for the macro-mini pouch vest was significantly higher than the single-layer pouch vest ($F(1,1679) = 56.48$, $p < .001$). We confirmed this result via a post-hoc pairwise comparison test with a Bonferroni correction ($p < .001$). This ANOVA also showed that there was a significant difference in the pouch location ($F(13,1679) = 34.42$, $p < .001$) and we again conducted a post-hoc pairwise comparison test with a Bonferroni correction to determine which pouches were significantly different from one another. The statistical significance for this post-hoc test can be found in Fig. 7(b). Lastly, this ANOVA showed that the reported radii was significantly different for each commanded pressure ($F(2,1679) = 195.93$, $p < .001$). A post-hoc pairwise comparison test with a Bonferroni correction confirmed that reported radii for 1.0 psi were significantly higher than for 0.5 psi ($p < .001$) and reported radii for 0.5 psi were significantly higher than for 0.3 psi ($p < .001$), indicating that increased pressure results in larger perceived contact area by participants.

3) Post-Study Survey: 18 out of the 20 participants stated that they preferred the macro-mini pouch vest to the single-layer pouch vest. When providing comments regarding the macro-mini pouch vest device, participants stated that it was "like a nice form fitting suit" and that they "liked that the device has a bit of a tighter fit" and was "easier to feel sensations." One participant stated that the device "applied pressure to a wider area" in comparison to the single pouch layer device. In contrast, when providing comments regarding the single pouch layer vest, participants stated that it "felt loose" and was "more difficult to feel the sensations." Participants stated that they "didn't feel the stimuli for a lot of the trials". Some participants specifically stated that they "never felt anything in the middle of their back" and another noted "it was easier to feel [sensations] closer to the shoulder." Lastly, some participants stated that the sensations from both of the devices felt "pleasant", "natural", or "like human touch."

E. Discussion

The user study results confirmed our hypotheses stemming from the work in [5]. From the analysis in Sec. III-D.1, we found that the detection thresholds for the macro-mini pouch device were not significantly different from the single-layer pouch device at pouch locations 1 and 14, but were significantly lower at pouch locations 5 and 9. Compared to the single-layer pouch device, the macro-mini pouch device was able to maintain strong contact with the curved middle and lower back (the curvature in the back created a larger height constraint as explored in [5]) using the inflated macro pouches, enabling participants to detect sensations at lower commanded pressures. We hypothesize that there was no significant difference between the devices at pouch location 1 because the vest is designed to rest on the shoulders, allowing pouch 1 to lay flat on the upper back at all times (smaller height constraint [5]). Similarly, we hypothesize that there was no significant difference at pouch location 14 because it was located close to the hips allowing both devices to fit tightly to the participant (smaller height constraint [5]) since the hips are often wider than the rest of the back, especially for women. Therefore, we can conclude that using one layer of pouches as a way to control effective displacement allows the wearable haptic device to better conform to the human body and allows the second layer of pouches to provide more salient stimuli.

From the analysis in Sec. III-D.2, we confirmed our hypothesis that participants could identify the location of the stimuli better with the macro-mini pouch device than the single-layer pouch device; the distances of the selected circle from the mean center were significantly smaller. A limitation of our study is that our analysis evaluates the distance from the calculated mean center as opposed to the distance from the actual location of the pouch. The pouches were in a fixed position on the vest and participants were of different shapes and sizes, so the pouches did not contact each participant in the exact same location and we asked participants to indicate on the figure where they felt the sensation. Additionally, the macro-mini pouch device provided significantly fewer instances when the participants could not perceive a sensation compared to the single-layer pouch device. From our analysis of the radii of circle object responses, we also confirmed that perceived contact area of the haptic feedback was larger for the macro-mini pouch device and that the perceived contact area increases as the commanded pressure increases. As was postulated in [5], compared to the single-layer pouch vest, the macro-mini approach of stacking pouches enables the control of contact area within a larger range, and specifically allows a higher maximum contact area than would occur with a single pouch. The macro-mini approach enables finer resolution of localized forces to be displayed which allows a larger range of haptic sensations to be rendered. Typically, if designers want to control the perceived contact area over which they exert a pressure, they need to actuate multiple individual tactors. However, with macro-mini actuation, we can actively control the perceived contact area through a single actuator.

Equally important to the quantitative results, the qualitative feedback from participants showcases their preference to the macro-mini pouch device over the single-layer pouch device. 90% of the participants stated that they preferred the macro-mini device and their open-ended feedback highlighted the improved fit and its ability to provide distinguishable haptic feedback. However, improvements can still be made to the device. While our pneumatic display is lightweight and conformable where the display contacts the user, it requires an air source, vacuum, and valves which are not lightweight or conformable. In future iterations of the device, we hope to use small pneumatic modules, such as FlowIO [9], to enable a lightweight, untethered device. Additionally, incorporating pressure sensors and force sensors for closed-loop control would likely improve the resulting perception of haptic stimuli and allow for a broader range of stimuli.

IV. Haptic Hug Demonstration

To demonstrate the ability of the macro-mini pouch haptic device to generate complex haptic stimuli with varying contact area and pressure on a large area, we measured a human-human hug and reproduced the pressure distribution.

A. Human-Human Hugging Interaction

For this demonstration, we recorded the pressure distribution of a bimanual frontal human-human hug between two participants. We recorded the spatial pressure distribution on one of the participants over the hug duration using a custom-designed pressure sensing vest, shown in Fig. 9(a). The vest was composed of custom soft capacitive sensor arrays (Pressure Profile Systems). The two flexible arrays were placed over the upper and lower back. Each array is composed of 1 in^2 (6.45 cm^2) cells, covering a total of 305 in^2 (0.197 m^2). The device has a 2.96 psi (20.4 kPa) range with 0.004 ± 0.001 psi (0.0276 ± 0.00689 kPa) resolution, and data was recorded at 20 Hz. The pressure sensing vest was fit to the participant by adjusting hook-and-loop fastener straps over the shoulders, chest, and waist.

B. Hug Analysis and Haptic Pressure Distribution

From the collected hug data, we observed two major patterns. Because of the bimanual nature of the hug, pressure concentrations were observed on the left and the right sides of the back. When hugging, participants either placed both their arms on the upper back or placed one arm on the upper back and the other arm on the lower back (contralateral). Based on these observations, we segmented the recorded

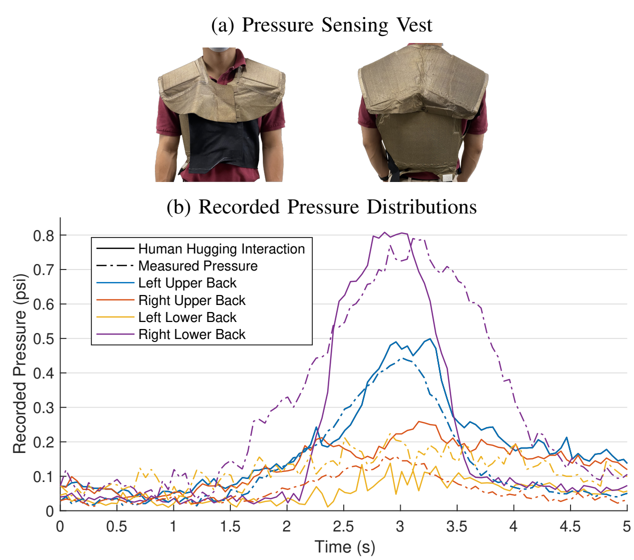

Fig. 9. (a) Pressure sensing vest. (b) Recorded human-human hug data shown by the solid lines and recorded pressure distribution generated by the macro-mini pouch device to mimic the hug data shown by the dotted lines.

pressure distribution data into four quadrants: the left upper back, right upper back, left lower back, and right lower back.

During a hug, most regions of the recipient's back are not in contact with the initiator's hands or arms and therefore no pressure is felt or recorded at those locations. We believe that the most salient sensations correspond to the locations with the greatest applied pressure. Accordingly, for each quadrant we selected the maximum pressure value at each time step from the cells within the quadrant, resulting in the 4 pressure profiles shown in solid lines in Fig. 9(b).

To create a haptic pressure distribution similar to the human hugging interaction, we overlaid the macro-mini pouch vest on the pressure sensing vest to align the pouches with the sensor cells. We then segmented the macro-mini pouch vest into 4 quadrants according to the 4 quadrants on the pressure sensing vest. Pouch 1 corresponded to the right upper back, pouch 3 to the left upper back, pouches 4 and 8 to the right lower back, and pouches 6 and 9 to the left lower back. Pouches 2 and 5 were at the left and right upper back. Pouches 7 and 10–14 were located off of the pressure sensing vest, so they were not included in any quadrant.

We manually tuned the commanded pressure profiles for each quadrant of the macro-mini pouch haptic device to match the recorded pressure profiles from the human hug. We used two separate QB3 pressure regulators to control the commanded pressure to the pouches in the left upper back quadrant and right lower back quadrant, respectively. Due to the lower stiffness of the macro-mini pouch haptic device compared to human touch, we could not measure the haptic hug while the human user wore the soft pressure sensing vest. Instead we recorded the pressure time series while the sensing vest and haptic device were stacked on a rigid flat surface (Fig. 9(b)).

C. Discussion

Figure 9(b) shows the results of the pressure distribution displayed by the macro-mini pouch device when placed on a rigid flat surface. The macro-mini pouch vest was able to reach the same pressure magnitudes as seen in the human-human hug data, with slightly increased rise and fall times.

The hand-tuned pressure profiles for each quadrant were also displayed to a user while they wore the macro-mini pouch device with the macro pouches inflated to fit to them. Although the pressure sensing vest could not record the pressure profiles while the macro-mini pouch device was worn by the user, the user reported feeling a strong and noticeable squeezing sensation reminiscent of the recorded hug.

The haptic hug demonstration is intended as a simple proof-of-concept demonstration for a sample application which requires the ability to convey varying pressures and contact areas to the human back. There are a number of ways to improve the generated pressure profiles, such as with further hand-tuning or using data driven methods [10]. Additionally, the device's macro-mini pouch actuator array configuration was designed to cover the entirety of the wearable housing to relay sensations to the human back; the position and sizing of the pouches could be optimized for hugging interactions.

V. Conclusions and Future Work

In this article, we presented soft, wearable haptic devices that use pneumatic arrays of single and stacked pouches to provide stimuli to the large area of the human back. We evaluated the devices with a human subject study and determined that participants have lower detection thresholds when they wear the device with macro-mini stacked pouches compared to the device with the single layer of pouches. We also determined that participants could identify the location of stimuli better with the macro-mini pouch device than the single layer device, and that their ability to localize the stimuli improves and the perceived contact area of the stimuli increases as the control pressure increases. Lastly, we demonstrated that these pneumatic pouches can be controlled to render sensations similar to what is felt during human-human hugging interactions. In future work, we hope to use this device to understand additional parameters involved in the perception of hugging, such as spacing between contact points and required resolution, as well as evaluate the device in providing additional forms of complex haptic feedback.

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