Design and Analysis of Pneumatic 2-DoF Soft Haptic Devices for Shear Display

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***Abstract*— Haptic devices use touch to enable communication in a salient and private manner. While most haptic devices are held or worn at the hand, there is recent interest in developing wearable haptic devices for the arms. This frees the hands for manipulation tasks, but creates challenges for wearability. One approach is to use pneumatically driven soft haptic devices that, compared to rigid devices, can be more readily worn due to their form factor and light weight. We propose a 2-degree of freedom (2-DOF) pneumatic soft linear tactor that can be mounted on the forearm and provide shear force. The tactor is comprised of four soft fiber-constrained linear pneumatic actuators connected to a dome-shaped tactor head. The tactor can provide fast, repeatable forces on the order of 1 N in shear, in various directions in the plane of the skin surface. We demonstrate the trade-offs of two housing schemes, one soft and one rigid, that mount the pneumatic soft linear actuator to the forearm. A user study demonstrated the performance of both versions of the device in providing directional cues, highlighting the challenges and importance of grounding soft wearable devices and the difficulties of designing haptic devices given the perceptual limits of the human forearm.**

Soft Material Robotics; Haptics and Haptic Interfaces

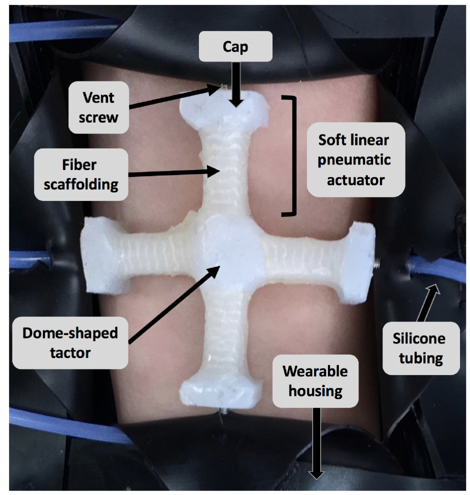

Fig. 1. A 2-DoF soft haptic device is comprised of four fiber-constrained linear pneumatic actuators connected to a dome-shaped tactor head, and attached to a flexible wearable housing.

I. Introduction

Haptics – the sense of touch – enables humans to perform a wide variety of exploration and manipulation tasks in the real world. In virtual worlds and robot teleoperation scenarios, this sense of touch must be artificially recreated by stimulating the human body in a manner that produces the salient features of touch needed to enhance realism and improve human performance.

Approaches from soft robotics are now being used to create wearable haptic devices that are safe, light weight, and provide a comfortable user experience. In this paper, we present a new wearable 2-DOF pneumatic soft linear tactor that can be mounted on the forearm and provide shear force, in the form of skin stretch, to the forearm. Each pneumatic linear soft actuator is light weight and easily fabricated. The device can provide skin stretch in eight directions in the plane of the arm. We present the device with two different housing schemes, rigid and soft. A user study, with 10 participants for each housing condition, was performed and indicates that four different direction cues can be distinguished at a rate better than chance for both designs and the rigid case had superior performance.

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II. Prior Work

Many wearable haptic devices have focused on stimulating the skin on the palms of the hands and fingertips because it is glabrous (non-hairy) skin; glabrous skin has higher sensitivity than hairy skin because of its higher density and different types of mechanoreceptors. However, most haptic devices mounted on the fingertips and hands inherently impede manual interactions with the user's environment. Instead, our device delivers feedback to the forearm, leaving the hands free to perform other manipulation tasks.

Wearable tactile devices on the forearm have been demonstrated to provide cues such as vibration and normal skin deformation [1], [2]. Both direction cues and learned vocabularies of tactile cues can be transmitted via forearm mounted devices [3], [4]. Bark et al. found that using shear forces on the arm provides superior and more intuitive directional feedback than vibrotactile feedback [5]. Biggs et al. showed that mechanoreceptors on the forearm are more sensitive to tangential forces than normal forces [6].

Skin stretch has been used to create convincing illusions of force feedback by providing shear forces to the skin on the fingertips. The literature has shown that skin shear can enable various tasks in virtual environments, such as mass perception [7], stiffness perception [8], and path-following [9]. However, we are aware of only two published results on wearable haptic devices that provide shear forces to the forearm: a fabric device that caresses the arm by applying shear forces [10] and the Haptic Rocker, which conveys learned haptic cues [11]. Our device is different because it can provide multiple degrees of freedom (DoF), the actuators are composed of soft materials, and it uses pneumatic actuation. Other wearable pneumatic actuators have provided accurate directional cues via normal forces on the wrist [12], [13]. However, our device achieves multiple DoF with a single contact point, whereas the former devices have multiple contact points, each with one DoF. Another difference is that the soft material in our haptic device is an extensible elastomer, whereas the other devices are flexible but not extensible.

There is significant research activity toward understanding the underlying mechanisms of skin stretch perception. Work by Pare et al. examined perceived magnitudes of shear forces from 0.15 to 0.7 N, and found that human perception of tangential force scales with the magnitude of the normal force applied [14]. A set of unpublished pilot studies performed by our research group found that 0.23 N of shear force applied with a Phantom Premium haptic device to the forearm is clearly perceivable (n = 17), and that just 1 mm of skin displacement at the forearm from a miniature 3-DoF tactor developed within the lab allows participants to identify the direction of a shear stimulus with an average error of 30 degrees (n = 10). Based on these previous studies, the soft haptic device created for this work was designed to provide a shear force between 0.2 and 1 N and have displacements of 1 to 5 mm, depending on the stiffness of the skin.

The main contribution of this work is a novel 2-DoF wearable pneumatic device that utilizes skin stretch, a promising and highly intuitive means of directional haptic feedback, while taking advantage of unused skin "real estate" on the forearm. Here, the synergy of soft robotics and haptics gives rise to a multi-degree-of-freedom device that provides wearable haptic communication.

III. HARDWARE

The pneumatic linear soft actuator is composed of three main components: the soft tactor, the wearable housing, and the pneumatic system. The soft tactor is mounted to the volar distal forearm using the housing. The tactor's movement along the skin is controlled by a pneumatic system. This section provides the details of the fabrication of the pneumatic soft linear actuator, its wearable housing, and the system architecture.

A. Soft Tactor

The soft tactor is made of four pre-stretched, soft, fiber-constrained linear pneumatic actuators arranged in a cross shape. These actuators, made of Ecoflex 00-30 silicone rubber, elongate with positive pressure. The design and manufacturing of this type of actuator is described in detail in [15], [16]. The actuators for our device have a chamber length of 12.3 mm, chosen to create an optimum stretch ratio of 1.5, while still fitting on the forearm.

At the center of the cross is a tactor head that is in contact with the user's forearm. The tactor head size and shape is customizable, and this device has a dome shape (radius 5.2 mm and height 4.4 mm) to maximize its area of contact with the skin and prevent edge effects. The tactor was chosen to be this size so that its contact area was large enough to be sufficiently noticeable but small enough to maximize the displacement of the linear pneumatic actuators. One end of each soft pneumatic actuator is attached to the dome, and the other end is attached to a housing via vent screws, which are hollow screws that allow pressurized air to flow into the pneumatic actuator.

Each of the four soft linear pneumatic actuators operates in one of two states: pressurized or depressurized. When the four actuators are pressurized and depressurized in various combinations, the tactor can stretch the skin in eight discrete directions in the plane of the skin. Figure 2 shows the eight directions of lateral movement that the soft tactor can achieve, and the corresponding actuation commands. When only one soft linear pneumatic actuator is pressurized, the tactor head moves along the major axis of that actuator (Figure 2 (a), (c), (e) and (g)). When two linear actuators are pressurized, the device moves in directions approximately 45 degrees off of the major axes (Figure 2 (b), (d), (f) and (h)).

B. Wearable housing

Two wearable housing designs, one soft and one rigid, were created to place the tactor in contact with the skin of the forearm and ground the haptic feedback.

1) Soft housing: The soft housing is an adjustable-size soft sleeve comprised of Shore A 90 hardness rubber. This rubber was selected to be soft enough to bend around the arm, but hard enough to provide reaction forces in order to hold the soft tactor in place. This housing is comprised of two parts. The first is a thin, flexible layer of 1/32 inch thick rubber that wraps around the forearm and is secured using Velcro. A layer of Dycem was adhered to the underside of this layer using MD 9000 double-sided adhesive in order to increase friction between the device and the user's arm. The second is a semi-rigid box-shaped frame made out of layers of 1/16 inch thick rubber that are adhered together using MD 9000 double-sided adhesive. The semi-rigid box is sewn onto the thin flexible layer via four flaps that lift up to expose a 48.8 $\times$ 48.8 mm square window. With this, the tactor can move in a flat 2D plane and be held to its pre-stretched length. The vent screws pass through a drilled hole in each flap and are secured to the housing using a nut. Silicone tubing for pneumatic control is passed through an

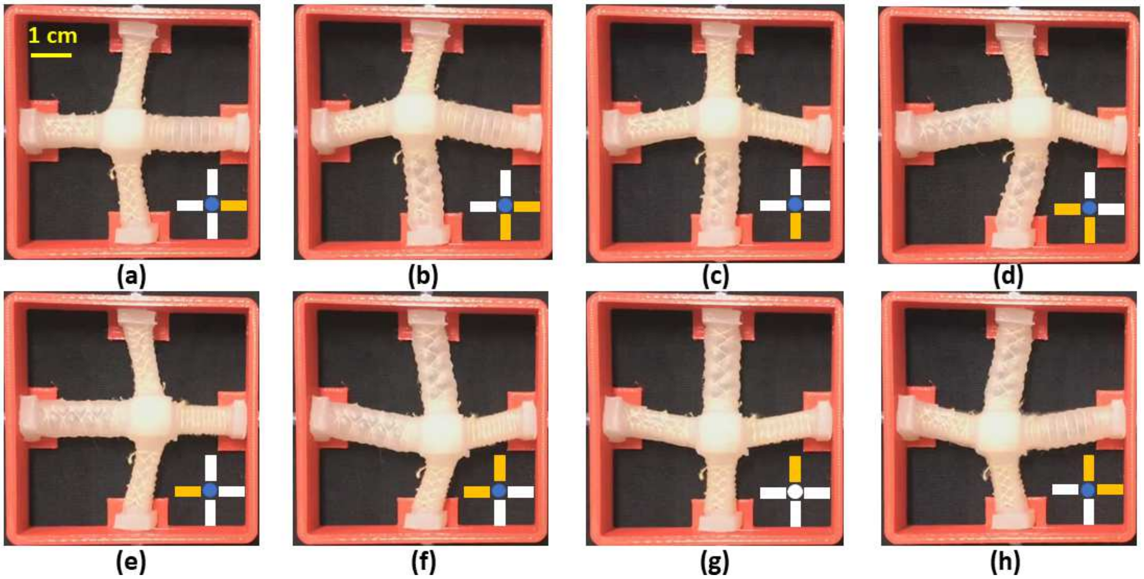

Fig. 2. Positions achieved by pressurizing and depressurizing various combinations of the soft linear pneumatic actuators. In the diagram in the bottom right hand corner of each image, the pressurized actuators are shown in yellow and the depressurized actuators are shown in white. The pressurized actuator compresses the unpressurized actuator, making the center tactor head move. The input pressure in these examples was 5 psi.

integrated hole in the flap. With this design, the housing can wrap around the forearm easily and the soft tactor has secure and consistent contact with the skin. Together, the soft tactor and housing unit weigh 150 g. Figure 3 (top) demonstrates how the soft haptic device is placed on a user's arm.

2) Rigid housing: The rigid housing was 3D printed using a Makerbot. The material used was polylactic acid (PLA) and the design is showed in Figure 3 (bottom). The housing is box shaped, measuring 48.8 $\times$ 48.8 mm. Each leg of the soft tactor is attached to each side of the box using an acrylic cap. The acrylic cap is placed over the wide head of the tactor and screws are used to tighten the cap over the linear actuator head, creating an airtight connection. There is another hole in the side of the wearable to allow the vent screw to pass through, which then connects to silicone tubing for pneumatic control. The rigid housing has holes for Velcro straps, which have a layer of Dycem adhered to the underside to increase friction for grounding.

C. System Architecture

Our soft haptic device hardware system includes an air pressure source, a power source, solenoid valves, a micro-controller unit, the housing, and the soft tactor. The air pressure source is a 150 psi wall supply with a 0.021 $\mathrm{dm}^3/(\mathrm{s}\cdot\mathrm{bar})$ flow rate. A pressure regulator drops the input pressure to each soft linear pneumatic actuator as desired. A pressure range of 5-10 psi was chosen based on past experience designing soft robots made with Ecoflex 00-30 silicone rubber. A Teensy 3.2 Board controls the 3-way/2-position miniature solenoid valves, SMC S070C-5CG-32, which direct and vent the pressurized air to the pneumatic linear soft actuators. These solenoid valves only have two states: open or closed. There is a solenoid valve for each linear actuator, for a total of 4 solenoid valves.

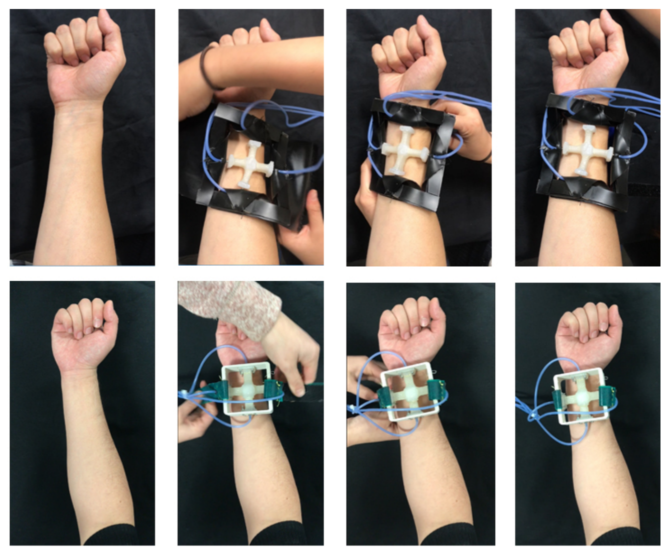

Fig. 3. The process of donning the wearable soft haptic device on a human arm for the soft housing (top) and the rigid housing (bottom).

IV. Device Performance

In this section, we present our investigation to maximize the tactor head displacement in free space and quantify the magnitude of the shear force produced by the soft tactor in all eight directions. These force production values are critical for characterizing the capabilities of our soft haptic device to provide skin stretch when in contact with the arm.

A. Initial Stretch Length

Previous research shows that users can detect the direction of stretch on the forearm more accurately with larger shear displacements on the skin [4]. As such, the displacement of our tactor head along each axis of the cross was maximized.

In its housing, the tactor head can be displaced approximately the distance it can expand plus the distance it is stretched. However, the displacement is limited by the compression force from the opposing soft pneumatic actuator. Additionally, the reliability of a pneumatic soft actuator degrades when it is stretched too much because of material limitations of the silicone rubber. Moreover, the overall size of the device's workspace is constrained by the dimensions of the smallest user's forearm.

To investigate the optimal initial stretch length of our soft actuator, we molded together two linear actuators to replicate one axis of the cross-shaped tactor. This was attached to a slotted stretching device that has slots 5 mm apart along its length and two detachable panels. The actuators are screwed into the panels which, when placed into different slots, stretch the linear pneumatic actuators to discretized, customizable lengths, as shown in Figure 4. When collecting the data, one of the linear pneumatic actuators was pressurized to 10 psi while the other remained depressurized, and the displacement of the connection point between the two actuators was measured using the video tracking program Tracker. Five stretch lengths were measured, and the results are shown in Figure 5.

The stretch ratio that led to the maximum displacement was 1.5. As the initial stretch ratio of the actuators increases from 1.1 to 1.5, the displacement increases, and beginning at 1.6, the displacement begins to decrease. At lower stretch ratios, the opposing linear actuator is not yet strongly resisting compression. At higher stretch ratios, the actuators are closer to their fully extended length, which may reduce their structural integrity and, consequently, the amount of force they apply. We note that the value of the maximum displacement depends in practice on the stiffness of the skin where forces are applied; the tests for displacement were performed in free space, whereas the shear force experiments described in the following section were performed with the force sensor which was rigidly grounded to the housing.

B. Shear Force Measurement

To measure the shear force applied by the soft haptic device, we mounted an ATI Nano17, a 6-axis Force/Torque sensor, onto the soft tactor head. The tactor was mounted such that the normal force of the Nano17 on the tactor was held constant at 1 N, which was chosen based on results from a pilot study where we measured the average normal forces applied manually by humans when stretching the skin to communicate direction.

Next, we recorded the shear forces from the sensor as the soft haptic device actuated in each of the eight different directions. Figure 6 shows the repeatability of our device through four cyclic measurements of the shear force data for one direction when the input was a 0.24 Hz square wave with an amplitude of 5 psi. Figure 7 summarizes the shear force output, given a square wave input, for all eight command directions at an pressure of 6.5 psi, the same amplitude used for the user study.

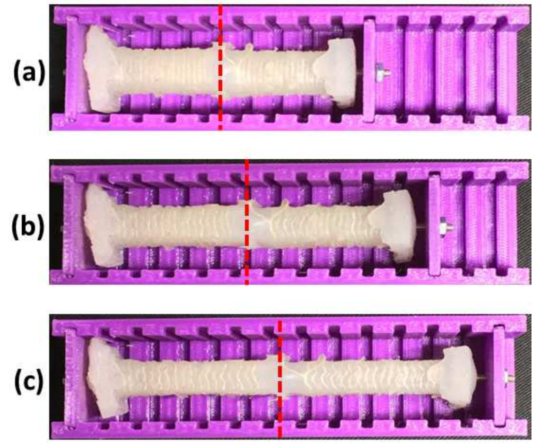

Fig. 4. System used to investigate the optimal initial stretch ratio of two soft actuators connected in series, in order to maximally move their connection point, which is indicated by a red dashed line. The optimal stretch ratio was determined by testing a series of initial stretch ratios to examine the competing factors of compressing a depressurized actuator and pressurizing the other actuator less than its maximum length. Examples of initial stretch ratios shown here are (a) 1, (b) 1.38, and (c) 1.64.

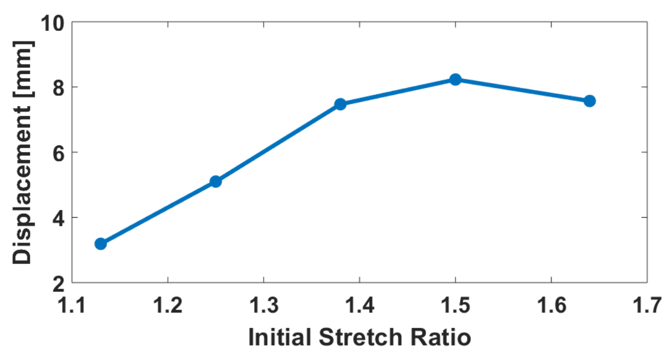

Fig. 5. Results of the displacement of the attachment point of two soft actuators for different initial stretch length ratios, which is the ratio of the stretch length after and before it is stretched.

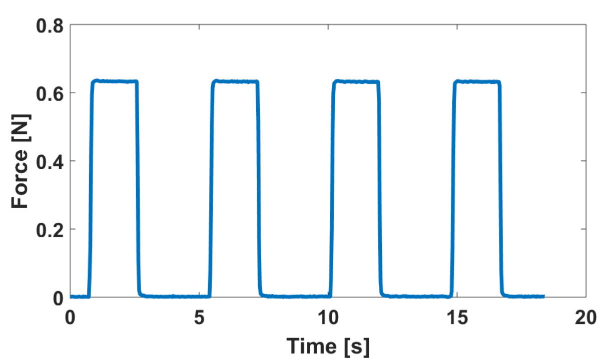

Fig. 6. Measured shear force response of the soft haptic device in a single direction. The input pressure is a square wave of 0.24 Hz and 5 psi.

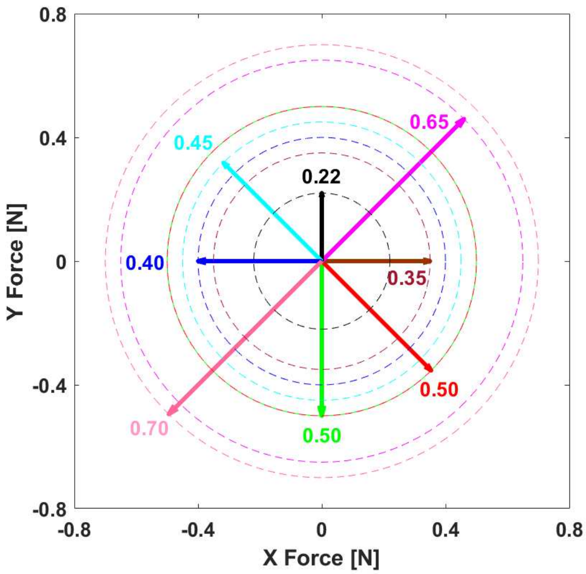

Fig. 7. Measured maximum shear forces of the soft haptic device with the rigid casing in 8 different command directions. The length and angle of the 8 different colored arrow-tipped lines represent the amplitude and command direction of the maximum shear force. For further visualization, the colored dashed circles show the magnitudes of the forces corresponding to their respectively colored arrow-tipped lines. The input pressure was 6.5 psi in each case.

The results show that the shear forces along the diagonals are larger than the forces along the principal directions. This is because when adjacent actuators are pressurized their forces superimpose to generate a larger force than that generated by a single actuator along the principal directions. The diagonal force is roughly equal to the vector sum of the two nearest linear actuators' forces. Due to inconsistencies inherent in the fabrication process, the shear forces from the different soft actuators have significant differences. However, pre-calibration or closed-loop control could be used to produce more even forces in future iterations of the device. The design and results in this paper use only open-loop control of the actuators.

V. User Study

A user study was conducted to determine if participants could identify directional cues provided by our pneumatic, forearm-mounted device. The study was carried out with both housing schemes in order to examine how a soft housing, rather than a rigid housing, impacts users' ability to infer direction cues through haptic skin stretch. The actuators used with each housing had the same design and fabrication process, except for the size of the cap, which was made wider to be screwed to the rigid housing and create an airtight seal. 20 right-handed users participated in the study, with 10 testing each device. 6 participants who used the soft housing and 6 participants who used the rigid housing study had previous experience with haptic devices, but none of the participants had any previous experience with our device. The experimental protocol was approved by the Stanford University Institutional Review Board, and all participants gave informed consent.

Fig. 8. User study setup, showing a participant wearing the device (hidden from sight behind a board), viewing the interface for prompts and responses, and wearing headphones to eliminate noise cues.

A. Study Methods

The devices used in this study consisted of the soft pneumatic actuator in a wearable housing (soft or rigid) and attached to its pneumatic hardware system.

Participants were asked to hold their right forearm out, palm up, and the device was attached to their volar distal forearm such that the tactor was centered across the width of their forearm as shown in Figures 3 and 8. The cross-shaped actuator was carefully positioned such that one axis was parallel to the length of the arm and the other ran perpendicular across the width of the user's wrist. The wearable housing was then attached firmly to the arm so that the soft tactor head made firm contact with the forearm, but the linear pneumatic actuators remained elevated above the skin and the user was comfortable. After the wearable straps were attached, the tactor was lifted gently above the skin and placed down on the user's forearm again so that movement from adjusting the wearable would not result in any residual shear force on the skin that would bias the data. The user then placed their arm with the device on a table in a manner that avoided pressing on the pneumatic tubes.

During the study, users were asked to select which direction they felt their skin stretch. The stimulus directions in this study were 0°, 90°, 180°, and 270°. 0° was defined as being stretched towards the elbow, 90° was laterally in the direction of the thumb, 180° was towards the user's hand, and 270° was laterally in the direction of the pinky finger. When a directional signal was applied, the corresponding pneumatic linear actuator combination was pressurized for 2.5 seconds so that the tactor would move to stretch the skin, and then depressurized so that the tactor head returned back to the center state. The actuator in the soft housing was pressurized to 10 psi while the actuator in the rigid housing was pressurized to 6.5 psi. The pressures differ because the device could not give produce the same shear force in the soft housing, compared to the rigid housing. As discussed earlier, this is because soft grounding cancels a portion of the actuation force and reduces the tactor displacement.

Before beginning the study, participants were shown how the device would actuate. They watched the device actuate 8 times, 2 times for each of the 4 directions. Then, the device was mounted on the user, they put on passive wear protection, and a barrier was placed between their input screen and the device as shown in Figure 8. First, the users iterated through 8 practice trials using a graphical user interface. Users clicked play when they were ready to be displayed a directional cue and recorded their selection when they were confident in their response. They were given the opportunity to repeat the signal up to 3 times and encouraged to repeat until they felt confident in their response. The users were then shown the correct angle selection on the screen. Before users could move to the next practice trial, they felt the directional cue again and needed to select the correct angle. These practice trials were included to help the participant gain comfort using and understanding the device. Next, the participants completed 20 experimental trials (5 actuations for each angle). Each participant received a unique, random permutation of the angles. Similar to the practice trials, participants iterated through the trials at their own pace, selecting when to play the signal, encouraged to repeat the signal (up to 3 times) until they were confident in their response, and they were ready to record their response. Participants were not given feedback pertaining to the correctness of their answers during the experiment. In total, 400 trials were performed across all subjects.

B. *Results*

The actuator with the rigid housing achieved an average accuracy across all four directions and all ten users of 86%. Three users achieved 100% accuracy and the user with the lowest accuracy achieved an average of 60%. In comparison, using the soft housing, users were able to identify the correct cue with an accuracy of 66.5%. The most accurate user was able to identify the correct angle in 95% of the trials, while the least accurate user was able to identify the correct angle in only 50% of the trials. We conducted a 2-sample t-test and confirmed that subjects were statistically significantly more accurate with the rigid housing design than the soft housing design ($p = 0.0045$). Futhermore, the rigid housing device showed only a 10% difference in average accuracy across the four directions, while the soft housing showed a 30% difference. There is no correlation between the two housings in terms of which direction was most accurately identified. The confusion matrix for the soft housing given in Figure 9 shows that most often when the participants were not selecting the correct angle, they were selecting an angle that was 180° out of phase with the intended angle. However, this was not the case for the actuator with rigid housing.

C. *Discussion*

The results from this user study offer two main contributions. The first is evaluation of our novel soft haptic wearable as a viable device for accurately communicating directional cues through skin stretch. The second contribution is to assess the difference in performance of the device with a soft housing compared to a rigid housing. In order to address the first point, we compare our device to other pneumatic devices mentioned in Section II. Our device achieves a lower user accuracy than the WRAP (99.4%) and the HAPWRAP (92.5%) [12], [13] with both the soft housing and the rigid housing. The results from our device also have a larger range across users. Between the most accurate user and the least accurate user, the range in accuracy was 45% with the soft housing and 40% with the rigid housing, compared to the HAPWRAP which had a range of 17.5%. One reason for this difference is that our device relies on shear force and skin stretch, rather than normal force. We believe that this makes the device more susceptible to user variations in factors such as skin stiffness, underlying musculature, and amount of arm hair. Given these vast differences in perception of shear force on the forearm from person to person, accurate direction-cue skin-stretch devices may require individualized designs or perceptual calibration methods. Another reason is that HAPWRAP relies on a distribution of different contact points, which can have the disadvantage of requiring a larger area of contact with skin.

Furthermore, our results suggest that even though the individual directions had a difference in shear force of up to 0.3 N, this did not seem to translate to a difference in perception of direction. There appears to be little correlation between accuracy in a direction and the force of that direction, other than in the 180° direction, which had the lowest user accuracy and the lowest force. This suggests that a more even force distribution is unlikely to be a significant factor in improving user accuracy. Lack of accuracy is likely to result from the previously identified factor of individual variance in user's skin. Essentially, our device appears to be capable of achieving user accuracy that is comparable to the previous wearable haptic devices for certain individuals, but it is subject to a higher degree of variance across users. This demonstrates that skin stretch at a single contact point on the forearm may be a less reliable mechanism for identifying haptic directional cues than normal force at different contact points.

In comparing the soft housing to the rigid housing, it is important to note the shortcomings and advantages that each wearable possesses. The soft housing is an entirely soft wearable device with no rigid parts which allows for a more comfortable user experience. However, the soft wearable was on average 19.5% less accurate than the rigid housing, and its lowest accuracy direction was 24% less accurate than the lowest accuracy of the rigid housing. We believe that this is due to grounding issues. Despite the Dycem layer on the underside of the wearable, users indicated in qualitative feedback that they felt the wearable housing move, which mislead them about the direction of the tactor. This result was also demonstrated in the quantitative results of the user study, shown in Figure 9, in that the angle that users most commonly mistook for the correct angle in all four cases was the angle that was 180° out of phase with the original, or in other words, the direction that the housing moved in due to reaction forces from the tactor on the

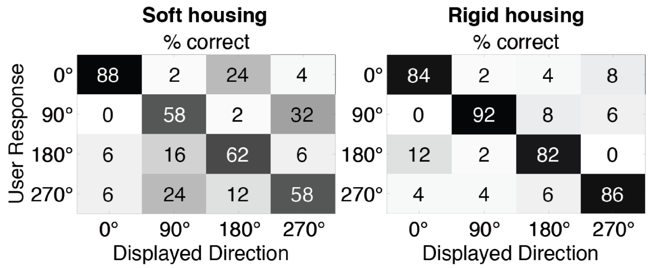

Fig. 9. Confusion matrices showing the percent correct responses for direction across all participants in the user study.

skin. Moreover, because the device was secured around the forearm, it provides more stability against the perpendicular force (up and down the forearm) than the torque (around the wrist) which could explain why identification of 0° and 180° was higher than the identification of 90° and 270° for the soft device. This 30° difference in accuracy suggests the importance of grounding of housing for wearable devices that communicate directional cues through skin stretch. Another weakness of the soft housing is that the connection of the soft tactor to the soft housing was difficult to make airtight because of the lack of rigid materials.

While the current design of the rigid housing is relatively bulky, it produced more accurate user results and it did not demonstrate the same errors in the opposite angles, which demonstrates that grounding was not an issue for the rigid housing. This suggests that increasing the stiffness of the housing was able to combat issues with reaction forces and provide better grounding. This highlights an issue with haptic devices that utilize shear forces: the wearable housing must be rigid enough to take into account non-trivial reaction forces in order to provide accurate haptic information. Future design iterations can focus on minimizing the bulkiness of the device, while still optimizing for performance.

VI. Conclusions

This article introduced a pneumatic wearable haptic device that is capable of executing lateral movements in a plane. We optimized its performance to maximize displacement and magnitude of shear force based on prior studies of human perception. The device can be attached to a housing to create a wearable shear display for the arm. We analyzed the performance of the soft pneumatic actuator with both a soft housing and a rigid housing. Participants in a user study were able to identify directional cues with an accuracy of 67% across four angles when using the device with the soft housing and with an accuracy of 86% when using the device with the rigid housing. This is slightly lower accuracy than for other soft haptic devices that convey direction cues through spatial distribution of haptic feedback via inflated pouches [12], [13], but our approach significantly decreases the footprint of the contact point(s) with the skin.

This work raises many interesting topics for immediate design and development of wearable soft haptic devices that display shear force, as well as long-term research. Most directly, our soft haptic device increases the user-detected accuracy by adding the rigid support material. Therefore, the combination of soft actuation and grounding using rigid materials is the preferable solution for soft wearable haptic device design. In future work, in order to get more scientific user study data, we also need to quantify the normal force, the shear force, and the displacements between the tactor and the human arm in the wearable configuration. Soft embedded sensing technology could be integrated to achieve this. Additionally, further fundamental studies about haptic perception on forearm are required; such studies can be performed with conventional haptic devices to better define the design requirements for wearable haptic devices.

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