Wearable Haptic Pneumatic Device for Creating the Illusion of Lateral Motion on the Arm

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Abstract—This paper presents the design of a novel haptic wearable device capable of creating the illusion of a continuous lateral motion on the forearm to mimic a stroking gesture commonly used in social touch. The device is composed of a fabric sleeve with a linear array of thermoplastic pneumatic actuators. The actuators are sequentially inflated and deflated, carefully controlling the amount of inflation of each actuator using an electronic pressure regulator. The travelling wave of pressure up the arm creates the illusion of lateral motion, even though no physical lateral motion occurs. We evaluate the device in a human-subject study to determine the optimal actuation parameters that create the most continuous and pleasant sensation. The results of the study indicate that short inflation times create a more continuous and pleasant sensation, but the pressure change during inflation does not affect continuity and pleasantness.

I. MOTIVATION

For decades, long-distance virtual communication has been limited to visual and auditory interactions. Limits in hardware and technology have prevented designers from providing fully immersive multi-sensory feedback in virtual reality (VR) or standard human-computer interaction (HCI) scenarios [1]. However, touch feedback can play a vital role in building a virtual world and increasing realism by matching the sensory feedback received when an individual interacts with people and objects in the physical world. Touch goes beyond just providing information about objects in the environment; it also conveys significant emotional information and is an important component of interpersonal communication [2]. For example, when your parents hold your hand and tell you that they love you, the temperature of their touch and reassuring pressure from their hand does just as much to convey their love as their words. These physical interactions make people feel more involved with the outside world or other individuals, since humans express a large range of emotions through touch [3]. However, most virtual communication systems lack the ability to recreate these rich, expressive touch signals [4].

As shown in [5], the potential areas of social touch cover a wide range of the body, depending on the social bond between the individuals. To match the complexity and realism of these social touch gestures, we argue that the haptic output device must be wearable and located on a part of the body where social touch is appropriate and commonly encountered. Pacchierotti et al. created a set of guidelines for creating wearable haptic devices for the hand [6], many of which can also be applied to devices worn on other parts of the body. Key guideline which must be considered are the device’s form factor, weight, comfort when worn, and degree to which it impairs normal movement.

There are several commercially-available wearable haptic devices on the market today that can display touch feedback to large areas of the body. The Rapture Vest, is an upper-body suit which provides point feedback through 8 actuators on the front body, 4 on each side [7]. A more advanced product is the whole-body Teslasuit, which consists of 60 actuators and 10 position sensors [8]. Teslasuit stimulates the sensory nerves when the current passes through the body by means of electrodes applied to the skin. This electrocutaneous feedback produces sensations that can vary from barely perceivable to highly unpleasant [9]. Researchers have also created large scale wearable haptic devices using arrays of vibration actuators [10]–[12]. Although these wearable devices can display a wide range of haptic cues to different parts of the body, one limitation they share is an inability to provide sensations that realistically mimic real-world touch cues. This realism is especially important when creating a device to match the emotional richness of social touch.

The motions used in social touch vary widely and can include gestures such as strokes, pokes, pats, and...
squeezes [13]. In this paper we focus on the creation of a haptic device to display a stroking sensation because this gesture can be used to convey a wide range of emotions including love, sadness, and sympathy [13]. Many previous haptic devices have been created for displaying a stroking sensation to a user. The simplest of these devices create a stroking sensation using direct lateral mechanical stimulation of the skin using a servo motor [14], an air jet [15], or parallel bars moved using a shape memory alloy actuator [16]. Moriyama et al. has also created a device for displaying the feeling of multiple fingers along the arm [17]. A stroking sensation can also be created through the use of haptic illusions, which has many benefits, including the ability to use mechanically simpler devices with less hardware. This reduced hardware is especially important when designing a wearable device. For example, vibration can be used to create the illusion of motion across the skin [18], [19]. This illusion has been used to create a stroking sensation in a haptic social touch device [20]. Recently, a new haptic illusion has been explored using sequential normal indentation to create the sensation of lateral motion in a social touch device [21]. This device was found to be both highly pleasant and continuous, but the actuator choice limits the scalability of the device.

This paper builds on the haptic illusion developed in [21], expanding on its utility through alternative hardware. Specifically, we create a wearable haptic device with pneumatic actuators with the goal of decreasing the device’s weight, improving motion impairment, and minimizing spacing between actuators. In addition to the flexibility of the pneumatic actuators increasing the wearability of the device, we hypothesize that the form of the actuators themselves would increase the continuity and pleasantness over the previous voice coil device. The voice coils provide only point stimulation, whereas the pneumatic actuators are designed to provide a consistent pressure across their entire surface area. We hypothesize that the increased surface area of the pressure will increase the continuity and better mimic the feeling of a hand moving across the arm. Furthermore, we predict that the ability of the actuators to deform to the arm will increase the pleasantness of the interaction. Traditional pneumatic actuators for haptic feedback are created using silicone. These actuators have been used to provide feedback for driving alerts [22], direction cues [23], and robotic surgery [24], [25]. Researchers have also created haptic pneumatic actuators using inelastic thermoplastic [26], [27].

In this paper we present the design of a novel haptic wearable device for creating the illusion of lateral motion on the arm. The device, shown in Fig. 1, is comprised of a linear array of thermoplastic pneumatic actuators, which are sequentially inflated. Section II presents the design and control of the device, and Section III evaluates the continuity and pleasantness of the stroking sensations created by the device in a human-subject study.

II. PNEUMATIC HAPTIC SLEEVE

The pneumatic haptic sleeve displays distributed pressure cues to a user’s arm. The device consists of six pneumatic actuators that are mounted in a linear array along a human forearm. This paper discusses how the actuators can be controlled to created the sensation of a lateral stroke along the arm. This section describes the design, manufacturing, and control of the pneumatic haptic sleeve.

A. Pneumatic Actuators

Because the device is wearable, it is important that the actuators themselves are lightweight, do not encumber the motion of the user, and are not noticeable when they are not inflated. For these reasons, we chose to make the actuators out of 0.002 inch-thick thermoplastic. This material is inelastic and can be easily formed to different shapes by applying heat. The inelastic material allows the actuators to inflate more quickly than traditional silicone pneumatic haptic actuators [23], and does not require fine closed-loop control of the actuation pressures.

As shown in Fig. 2, the actuators are created with a three-channel switchback design with an inlet and outlet tube. This design of actuators has previously been shown to be effective at quickly displaying noticeable directional cues [26]. The switchback design allows the actuator to remain flat when inflated, ensuring that the user receives the same amount of pressure at every location on the large surface area of the actuator. One tube is connected to the inlet of the channel; the air flows through the actuator, inflating it, before exiting through a second tube that vents to the environment. The external pressure from the fabric cover forces the air from the actuators, causing them to deflate when the air source is removed. The flow of the air through the actuator is controlled by a series of air pressure regulators and valves.

The length of the actuator is 63.5 mm and its width is 57 mm. The actuators have a channel width of 17 mm. To create the actuators, two sheets of thermoplastic are cut to the desired size and shape. Using a 2 mm-wide heat sealer, the layers are joined together to form the dividers between...
the channels. After the channels are created, the edges of the actuator are sealed, leaving only two small openings for the inlet and outlet tubes. The tubes are inserted into these openings and sealed with a combination of tape and glue.

B. Wearable Device

To make the wearable device comfortable and adjustable to multiple users, we build it in two steps: the sleeve and the actuator cover. This two-step design allows us to use a single set of actuators for all users, ensuring consistency of the haptic sensations.

1) Sleeve: Since we expect to encounter large variations in arm size in our user population, we must make our wearable sleeve adjustable to fit a large range of adult arm sizes. Furthermore, we expect that the sensation provided by our device will be affected by the tightness of the device on the arm, so the sleeve design must ensure that tightness can be kept consistent across users. A single sleeve made from a highly stretchable material would not maintain a consistent level of tightness across users. Therefore, we created three sleeves in small, medium, and large sizes.

The sleeves were constructed from a moderate-stretch cotton fabric to be breathable and conform to the user’s arm. The shape of the sleeves was designed based on ergonomics, being smaller towards the wrist and larger towards the elbow. This design ensures that the sleeve will comfortably fit the user along their whole arm. Two strips of velcro were attached to the bottom left and right of the sleeve for attaching the actuator cover.

2) Actuator Cover: The actuator cover consists of a fabric cover and the six actuators, and is attached to the outside of the fabric sleeve. The actuators are attached in a line down the center of the cover using tape. Each actuator overlaps with the neighboring actuator by 50%, as shown in Fig. 1. To ensure consistent inflation and deflation of the actuators, the inlet and outlet tubes must be kept from twisting. Therefore, the cover is created with velcro strips that thread through the tubes to maintain their alignment and attach the cover to the sleeve, as shown in Fig. 3.

C. Actuator Control

The pneumatic pouches are actuated by filling them with air from a pressurized air source. They deflate by passively venting the air to the environment. Fig. 4 shows the flow diagram for the actuation system. The system can be actuated using any pressurized air source, including a compressor; in our implementation we use pressurized air from an external dedicated source through the wall. Past systems with a similar actuator design used constant pressure air to inflate the actuators [26]. However, we aim to create signals with more variability and allow for gradual inflation with the goal of creating a lateral stroking sensation using an array of actuators. Therefore, our system requires accurate pressure control of the air used for inflation.

The air from the source is divided between two electronically controlled pressure regulators with a regulating range of 1-17 psi (Type 500-AF, ControlAir Inc.). A digital output signal from an Arduino Uno microcontroller sets the commanded pressure. The system in this paper requires only two pressure regulators because we inflate only two actuators at a single time. However, if different actuation patterns are used, then additional pressure regulators may be required.

Each pressure regulator controls the inflation of three actuators. As shown in Fig. 4, the actuators are alternated such that adjacent actuators are not fed by air from the same regulator. A set of solenoid valves (Isonic V1B04-BW1) direct the airflow into individual actuators and are controlled by the microcontroller.
To create the illusion of lateral motion, we build on the work done in [21], which created a similar sensation using a linear array of voicecoils controlled to sequentially indent the arm. Similar to this prior work, we use the pneumatic actuators to provide sequential pressure to the user’s arm. Fig. 5 shows the actuation signals for the linear array of six actuators. When the stroke begins, the first actuator is inflated with a linearly increasing air pressure from a set minimum to maximum pressure. When the air pressure reaches its maximum, the pressure is linearly decreased, and the second actuator begins its inflation following the same profile. The inflation pattern with 50% delay between actuators continues until reaching the final (sixth) actuator.

A previous study with the voicecoil system showed that large amounts of overlap of the pressure profiles of adjacent actuators increases continuity of the illusory motion [21]. Therefore, we designed the actuator array with 50% physical overlap between the actuators to produce no gaps between the pressure sensations.

III. HUMAN SUBJECT EXPERIMENT

We conducted a user study to test the realism of the lateral stroke sensation and to determine the best parameters for creating the most continuous and pleasant sensation. Ten participants were recruited to complete our study (8 males and 2 females, ages 23–29). Nine participants had no experience with haptic devices while one of had some prior experience. Thus, we consider this group of subjects to be representative of the user population of our device. The study protocol was approved by the University of Southern California Institutional Review Board and all participants gave informed consent.

A. Experimental Setup

Prior to the study, the participant’s wrist was measured to select the appropriate sleeve size to ensure consistent tightness and comfort. If their wrist circumference was less than 17 cm, the participant was given the small sleeve. If their wrist circumference was greater than 17 cm and less than 21 cm, they were given the medium sleeve. If their wrist circumference exceeded 21 cm, they were given the large sleeve. The sleeve was worn comfortably in the center of the participant’s non-dominant forearm with the seam-side down. The actuators were then attached to the top of the sleeve with the velcro straps, ensuring that the actuators lay in a straight line along the top of the arm.

The participant completed the study while seated with their arm resting flat on the table, actuators oriented upward. To prevent external auditory and visual cues (e.g. the sound of solenoid valves, air flow and surrounding noises, voltage values, and the light of the Arduino), participants wore noise-cancelling headphones and a divider blocked the system and electronics from view.

B. Experimental Parameters

In the study, we varied the control signals sent to the actuators to determine which combination of pressure values (high and low) and inflation times created the most continuous and pleasant lateral stroking sensation. We tested a total of six functions following the same pressure profile shown in Fig. 5. The parameters for these six functions are shown in Table I, where $t_I$ is the total inflation time for each actuator, $A_{\text{min}}$ is the minimum air pressure, and $A_{\text{max}}$ is the maximum air pressure. A nonzero minimum pressure was needed due to hardware limitations of the pressure regulator and the design of the sleeve itself. The sleeve could not be too tight on the user’s arm or it would restrict the flow of air into the actuator. This resulted in a small gap between the actuator and the user’s arm, and a minimum pressure was needed before the user could feel the actuator. We empirically determined this minimum pressure to be 6 psi.

<table>
<thead>
<tr>
<th>Function</th>
<th>$t_I$ (ms)</th>
<th>$A_{\text{min}}$ (psi)</th>
<th>$A_{\text{max}}$ (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function0</td>
<td>120</td>
<td>5.95</td>
<td>11.59</td>
</tr>
<tr>
<td>Function1</td>
<td>240</td>
<td>5.95</td>
<td>11.59</td>
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<tr>
<td>Function2</td>
<td>480</td>
<td>5.95</td>
<td>11.59</td>
</tr>
<tr>
<td>Function3</td>
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<td>5.02</td>
<td>6.65</td>
</tr>
<tr>
<td>Function4</td>
<td>240</td>
<td>5.02</td>
<td>6.65</td>
</tr>
<tr>
<td>Function5</td>
<td>480</td>
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C. Experimental Procedure

The experiment consisted of two phases. Phase 1 was a training phase where each participant felt the six pre-programmed actuation functions in pseudo-random order. In Phase 2, participants felt each actuation function one at a time. Each function was repeated three times and the order of all trials was randomized. After feeling each function, participants were asked to rate it on its perceived continuity, pleasantness, and ease of distinguishing the stroke. Participants rated continuity on a 5-point Likert scale where -2=Discrete and 2=Continuous, pleasantness on a 5-point Likert scale where -2=Unpleasant and 2=Pleasant, and the
ease of distinguishing the stroke on a 5-point Likert scale where -2=Difficult and 2=Easy. Participants verbally gave their responses, which were recorded by the experimenter.

D. Results

Fig. 6 shows the rated continuity for the six functions. We performed a two-way repeated-measures ANOVA on the continuity ratings with inflation time and maximum pressure as factors. Mauchly’s test indicated that assumptions of sphericity were not violated. The ANOVA showed that continuity ratings were statistically different across the inflation times ($F(2,55) = 32.3$, $p < 0.001$, $d = 0.52$), but were not significantly different across the maximum pressures ($F(1,55) = 0.19$, $p = 0.66$, $d = 0.002$). We ran a post-hoc pairwise comparison test with a Bonferroni correction to further evaluate the differences between the inflation times. Continuity ratings were significantly different for all pairs of inflation times ($p < 0.001$). Furthermore, rated continuity consistently decreases with increasing inflation time.

Fig. 7 shows the rated pleasantness for the six functions. We performed a two-way repeated-measures ANOVA on the pleasantness ratings with inflation time and maximum pressure as factors. Mauchly’s test indicated that assumptions of sphericity were not violated. The ANOVA showed that pleasantness ratings were statistically different across the inflation times ($F(2,55) = 3.98$, $p = 0.01$, $d = 0.02$), but not across the maximum pressures ($F(1,55) = 2.14$, $p = 0.18$, $d = 0.007$). We ran a post-hoc pairwise comparison test with a Bonferroni correction to further evaluate the differences between inflation times. Pleasantness ratings were significantly larger for inflation times of 120 ms than 480 ms ($p = 0.011$). Although there was a consistent trend of decreasing pleasantness with increasing inflation time, no other pairs were significantly different.

Fig. 8 shows the rated ease of distinguishing the stroke for the six functions, which is a measure of how perceivable the sensation was. We performed a two-way repeated measures ANOVA on the distinguishability ratings with inflation time and maximum pressure as factors. Mauchly’s test indicated that assumptions of sphericity were not violated. The ANOVA showed that distinguishability ratings were statistically different across maximum pressure ($F(1,55) = 4.25$, $p = 0.034$, $d = 0.18$). Inflation time was not a significant factor ($F(2,55) = 0.14$, $p = 0.87$, $d = 0.008$).

E. Discussion

The high continuity ratings show the success of our system in recreating the haptic illusion first presented in [21]. Although the illusion of lateral motion was originally created using sequential normal indentation via voice coils, our new system creates a similar pressure profile on the arm using an array of pneumatic actuators. The pneumatic actuators overlap, providing a more continuous pressure profile that can better mimic the sensation of a hand stroking the arm.
Comparing the average ratings of the best signal for this device to those for the previous voice coil device, adjusting for different numerical rating scales, we find that this device performed better for both continuity ($Cont_{\text{pneu}} = 1.3$, $Cont_{\text{vc}} = 1.1$) and pleasantness ($Pleas_{\text{pneu}} = 0.83$, $Pleas_{\text{vc}} = 0.52$). This pneumatic system has a further benefit of being more lightweight and less cumbersome.

The results of the study indicate that the perceived continuity and pleasantness of the stroking sensation decreased with increasing inflation time. Both measures were highest for the smallest inflation time of 120 ms. Therefore, to create the most continuous and pleasant stroking sensation, the inflation time should be minimized. However, the system requires a minimum inflation time due to the actuator size and the passive deflation process. The minimum inflation time could be further decreased if higher pressure air was used or if we added an active deflation system using a vacuum.

The study did not show any significant difference in either the rated continuity or pleasantness between the two maximum pressures. Although increasing the maximum pressure, and therefore the degree to which the actuators are inflated, can increase the perceivability of the stroking sensation, it does not change the effectiveness of the haptic illusion.

F. Conclusion and Future Work

In this paper we presented the design of a wearable device to create the sensation of a continuous lateral stroking sensation on the forearm. The device is composed of an array of thermoplastic pneumatic actuators in a fabric sleeve. The actuators are controlled to sequentially inflate, presenting a point of pressure that travels along the user’s arm to create the illusion of lateral motion. We evaluated the device in a human-subject study and determined that the inflation time of each individual actuator should be minimized to create the most pleasant and continuous sensation.

In this study, we kept delay between actuators at a constant 50% due to limitations in the hardware. However, it is likely that the delay would also have an effect on both continuity and pleasantness, as was shown in a previous study with a different device [21]. Therefore, in the future we plan to alter the control hardware to include a single pressure regulator for each actuator. This would allow us to set an arbitrary delay between actuators, and we could further evaluate the effects of delay with this device.

REFERENCES


