A Social Haptic Device to Create Continuous Lateral Motion Using Sequential Normal Indentation

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***Abstract*— Touch is an essential method for communicating emotions between individuals. Humans use a variety of different gestures to convey these emotions, including squeezes, pats, and strokes. This paper presents a device for creating a continuous lateral motion on the arm to mimic a subset of the gestures used in social touch. The device is composed of a linear array of voice coil actuators that is embedded in a fabric sleeve. The voice coils are controlled to sequentially press into the user's arm to create the sensation of linear travel up the arm. We evaluate the device in a human-subject study to confirm that a linear lateral motion can be created using only normal force, and to determine the optimal actuation parameters for creating a continuous and pleasant sensation. The results of the study indicated that the voice coils should be controlled with a long duration for each indentation and a short delay between the onset of indentation between adjacent actuators to maximize both continuity and pleasantness.**

I. Motivation

Touch is the primary nonverbal means of communication of emotion between humans [1]. Both our physical and emotional well-being relies on human-human touch, yet most computer-mediated interactions currently lack rich, meaningful touch signals [2].

Humans sense touch through specialized cells known as mechanoreceptors, which are embedded in the skin. Each mechanoreceptor senses and responds to a specific form of haptic stimulus: Pacinian corpuscles respond to high-frequency vibrations, Meissner corpuscles sense the rate of skin deformation, Merkel disks detect spatial features, and Ruffini endings sense skin stretch [3]. The presence and distribution of mechanoreceptors differs in hairy and non-hairy skin. Recent research has shown that an additional mechanoreceptor, the C tactile (CT) afferent, exists in hairy skin and selectively responds to stroking motions [4]. The CT afferents respond maximally to stroking in the range of 1-10 cm/s, which has also been shown to be the most pleasant range of velocities for stroking on the skin [5]. Results from a previous study by Hertenstein et al. indicated that stroking was a common gesture for conveying love, sympathy, and sadness [6]. Previous studies have also shown that individuals can successfully differentiate emotions when expressed solely through touch [6], [7], [8]. This result shows promise for the field of social haptics, which seeks to convey or elicit emotions through artificial means.

Fig. 1. Device for creating the sensation of continuous lateral motion using sequential indentation. A linear array of voice coils are controlled to apply a pre-determined indentation profile to the arm.

Many haptic devices previously designed for social touch seek to replicate a specific interaction or gesture, such as a hug [9], [10] or handshake [11]. Other social haptic systems make use of mediated social touch to transmit touch signals from one user to another over a distance [12]. In mediated social touch, the output signal can either be a direct replication of the input signal (e.g. [13]) or a mapping between different modalities (e.g. force input to vibration output [14]). A key component of social haptic devices is the design of the output hardware to display the social

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touch cues to the user. Previous researchers have shown that vibrations [15], [16], thermal displays [17], and air puffs [18] can be used to elicit an affective response, even though these modalities do not directly stimulate the CT afferents [19]. In this paper, we focus on the creation of a stroking sensation on the arm in an attempt to selectively activate the CT afferents and to recreate a common social touch gesture using voice coil motors (Fig. 1).

Many previous social devices have been designed for creating a stroking sensation using a range of different modalities of haptic stimulation. Several researchers have explored directly stimulating the skin using lateral motion generated by a servo motor [20] and by parallel bars controlled using shape memory alloy actuators [21]. A stroking sensation has also been created through indirect contact with the skin using an air jet [18]. The illusion of motion across the skin can also be created using vibration [22], [23], which has been used to simulate a stroking sensation in a social haptic device [16]. The use of haptic illusions is a promising method for creating a stroking sensation because it can create longer strokes than a physical tactor dragged across the skin with significantly lower mechanical complexity. However, there has been limited investigation into the use of normal force in the creation of the illusion of a stroking sensation.

We present the design of a novel wearable haptic device for creating a stroking sensation on the arm. The device, shown in Fig. 1, is comprised of a linear array of voice coils, which are used to sequentially indent the arm. 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. Device Design

This section describes the design and actuation of a wearable device for creating the sensation of lateral motion up the arm using only normal indentation. We begin by describing how this sensation was first prototyped using haptic sketching. We then present the final hardware design and actuation signals.

A. Haptic Sketch Prototype

We explored a variety of methods for creating the sensation of lateral motion on the skin by creating simple hand-actuated mechanical prototypes. These prototypes were created following the principles of haptic sketching, which were introduced by Moussette [24]. The goal of haptic sketching is to rapidly prototype haptic devices and effects with an emphasis on iteration rather than technical complexity. We used readily available materials that are easy to work with. We designed ten haptic sketches that used no electrical components and required the user to manually stimulate the skin using the device.

The haptic sketches we designed attempted to create lateral motion sensation through a variety of approaches. Several of the sketches involved significant movement of contact points by rolling and dragging contacts over the skin. These sketches were particularly helpful for considerations such as the amount of pressure/shear force and extent of movement, but were not likely to yield practical device designs for social touch. Other sketches used arrays of contacts with each contact point moving a relatively small distance normal or tangential to the skin. We felt that such arrays were more likely to be realizable in a wearable form factor in the long term. In addition, we used pressurized air applied to templates with arrays of holes to prototype different spacing and contact areas.

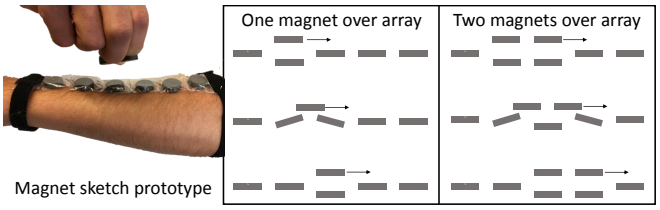

Fig. 2. Haptic sketch prototype using magnets. Diagrams show behavior of magnets in array when one or two repulsive magnets are used.

The haptic sketch that created the most pleasant and continuous sensation of lateral motion along the arm was a linear array of magnets attached to the arm using velcro straps, which displayed a distributed pattern of normal force (Fig. 2). The permanent magnets on the skin were all oriented with their north pole upwards, and we used a second permanent magnet oriented with its north pole downwards to repel the magnets into the skin. We held the free magnet above the array and manually scanned the free magnet across the array, sequentially pressing the other magnets into the skin. Fig. 2 shows the behavior of the magnets in the array if a single magnet or if two magnets were scanned over the array. A single magnet created a more localized contact point that felt similar to a finger dragging on the arm. Two magnets created a wider contact area, which felt more like several fingers or the whole hand dragging on the arm.

B. Electro-Mechanical Hardware

The success of the haptic sketch with magnets showed that the concept of using normal indentation to create the sensation of lateral motion up the arm was a promising direction. We expanded on this idea to create an electro-mechanical prototype of the system to allow us to easily vary the system's behavior and determine which parameters created the most pleasant and continuous sensation.

We measured the amount of normal force each magnet exerted on the arm in the sketch prototype to be in the range of 1-2 N. This level of force was both perceptible and comfortable on the arm. In a previous study, researchers experimentally determined that 1 N of force generated with magnetic repulsion would be sufficient for effective normal stimulation [25]. Thus, we selected our actuator such that it produced the minimum 1 N of normal force to be effective, and could consistently produce 1-2 N of normal force such that the sensation would be pleasant.

To maximize our design for wearability, the actuator used must be small and lightweight. Creating a wearable device is important to enable the natural arm postures used in

the device evaluation in Section III. We do not address mobility in this paper, which is ultimately limited by the power required by the actuators. In addition to being small in diameter to maximize the spatial resolution of the device, the actuator must also have a low profile so the device is not unwieldy and does not encumber the user's motion. The actuator must also have a reasonable stroke length so as to be easily perceptible by the user.

We chose a voice coil (Tectronic Elements TEAX19C01-8) actuated at low frequencies (< 5 Hz) to apply pressure directly to the skin because we could directly control the amount of skin deformation. Although this actuator has a large diameter (33 mm), which limits spatial resolution, it has a low vertical profile (12.8 mm) and reasonable mass (29 g) to be used in a wearable device. In our tests, we measured a stroke of ≈ 4 mm at the actuator's maximum rated current. This stroke is above the 1.5 mm depth of skin indentation shown in [26] to be consistently and accurately perceived by a user, indicating that this stroke length is sufficient for our device.

C. Mounting System

We created a linear array of voice coils to display indentation forces distributed in both location and time. Our design constraints in creating a method for attaching the voice coils to the arm were that the device should be lightweight, be comfortable to wear, not impede motion, be adjustable to fit different sized arms, and not substantially affect the signal displayed by the actuator. We tested both rigid and flexible systems and determined that a flexible mounting system resulted in the most strongly perceived indentation sensations.

We designed and built the actuator sleeve shown in Fig. 1. The sleeve is made of elastic fabric for comfort and adjustability. During our initial tests of the sleeve, we determined that it was necessary for the portion of the sleeve directly above the actuators to be inelastic so that the force from the actuators is directed downwards. If this portion is elastic, the actuators would move upwards and stretch the fabric such that the force the user feels is significantly decreased. To prevent this, an inelastic, but flexible, canvas patch was added down the middle of the sleeve. Velcro was added to attach the sleeve to the user's arm and to adjust the sleeve to fit differently sized arms. The sleeve can either be attached to the forearm or the upper arm, as shown in Fig. 6.

By default, the voice coils have a thin annular ring on the portion that contacts the skin. This contact can be uncomfortable and leads to less natural and pleasant sensations. We added a thin polypropylene cover to the tactor to create consistent contact and evenly distribute the force to the skin. The outside of the voice coils were covered in sleeves made of electrical rubber tape to thermally and electrically insulate the actuators from the user's skin.

D. Indentation Actuation Signals

The array of voice coils creates the sensation of a stroke up the arm by sequentially indenting the actuators into the arm. The stroke sensation can be controlled by varying the duration of the indentation (pulse width) and the amount of delay between the onset of indentation for adjacent actuators.

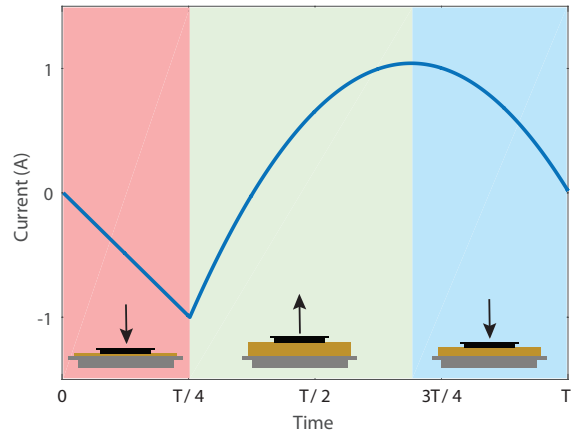

Fig. 3. Signal to control the motion of the voice coil. First, the tactor is retracted from the skin. Next, the tactor is indented into the skin following a quadratic profile. Finally, the tactor retracts and returns to its resting point just touching the skin.

When the actuator sleeve is worn on the arm, the tactors are always in contact with the skin. Our tests with the voice coils demonstrated that in order to create a strong normal force sensation, the tactor must first be retracted from the skin before the indentation. This retraction creates a longer effective stroke and results in a more noticeable indentation. As shown in Fig. 3, after the tactor is retracted, it is indented into the skin following a quadratic profile with the equation:

$$I(t) = a_{\text{vc}} \left(-\frac{32}{3T^2} t^2 + \frac{44}{3T} t - 4 \right) \tag{1}$$

where I is the current sent to the actuator, a_{vc} is the maximum current, T is the pulse width, and t is the time elapsed since the beginning of the indentation. This quadratic profile was fit by setting the beginning and ending current values ($I(T/4) = -a_{\text{vc}}$, $I(T) = 0$).

The actuators in the array are sequentially activated using the same signal with a set amount of delay between the onset of the indentation for adjacent actuators. The effect of this delay can be seen in Fig. 4. The signals on the left are delayed by 12.5% of the pulse width, which results in indentations that significantly overlap. The signals on the right are delayed by 75% of the pulse width, which results in indentations that are more disconnected. We study the effects of this delay between actuators on the perceived continuity and pleasantness of the stroke in Section III.

The voice coils are driven using an analog signal from a Sensoray 826 PCI card. Each voice coil is driven by a separate analog output pin on the Sensoray board, and the signals are updated at 1000 Hz. The signals are then passed through a custom-built linear current amplifier using a power op-amp (LM675T) with a gain of 1 A/V. The maximum current sent to the voice coils is limited to 1 A so as not to exceed their maximum rated power of 3 W RMS. The

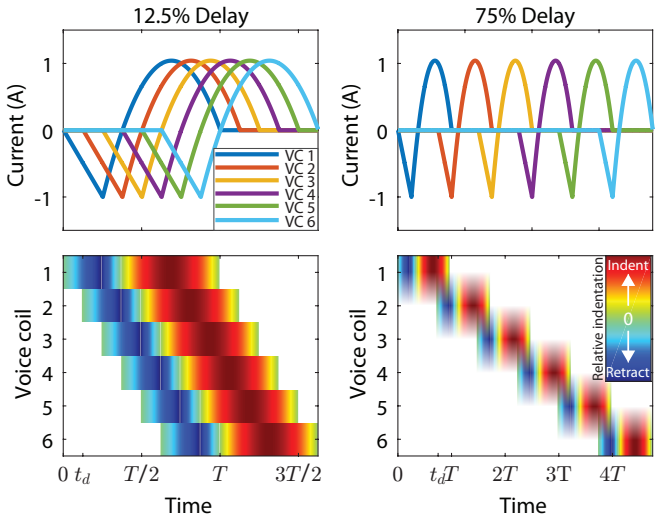

Fig. 4. (top) Sequential control signals for multiple actuators for 12.5% delay and 75% delay. (bottom) Indentation profile on skin over time. Shorter delays result in more overlap of the indentations. Longer delays result in more discrete indentations.

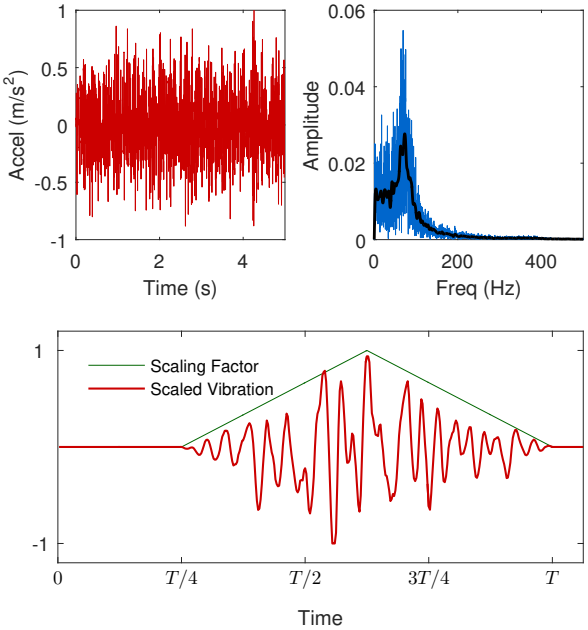

Fig. 5. Vibration signal. (top) Vibration synthesized from recording of leather. (bottom) Vibration scaled based on indentation depth.

voice coils produce some sound when actuated, although the overall sound level is low.

E. Vibration

Dragging contact on skin generates vibrations in addition to normal and tangential forces. Therefore, we added vibrations that more closely matched the vibrations generated from skin-skin contact. Borrowing from the approach of texture vibration modeling [27], we overlaid vibrations recorded from a leather sample that was included in the Penn Haptic Texture Toolkit [28]. The vibration signal and frequencies are shown in Fig. 5.

Previous research has shown that vibrations alone can be used to create the sensation of lateral motion [22], [29]. We tested different vibration scaling patterns to find which one created the most realistic and pleasant sensations. Playing constant amplitude vibration during the indentation phase created a pleasant sensation, but it felt artificial and reduced continuity. The most successful scaling pattern was the linear pattern shown in Fig. 5. The amplitude of the vibration was increased while the actuator was moving downward into the skin, and decreased while the actuator was moving upward away from the skin. This pattern felt pleasant and created the sensation of flow up the arm when played alone without the indentations.

The amplitude of the vibrations altered their effect on the continuity, pleasantness, and realism of the interaction. Higher amplitude vibrations created a larger increase in continuity, but degraded pleasantness and made the interaction feel more artificial. Lower amplitude vibrations were ultimately chosen because they still created a perceivable flow sensation, but did not create the same sense of artificiality of the higher amplitude vibration. The output vibrations were scaled to have a maximum current of 50 mA.

Fig. 6. Study setup. Participants completed the study wearing the device alternately on their lower and upper arm.

III. User Study

To determine which actuation parameters created the most continuous motion up the arm, as well as which parameters created the most pleasant sensation for the user, we performed a human-subject study under a wide range of actuation conditions. Sixteen participants (15 right-handed, 1 left-handed; 6 male, 10 female) participated in the study. Five of the participants had prior experience with haptic devices and eleven did not. The protocol was approved by the Stanford University Institutional Review Board, and all subjects gave informed consent.

A. Methods

Participants in the study sat at a table, as shown in Fig. 6. They wore headphones playing white noise to block sounds produced by the actuators.

Participants completed the study in two phases: one phase wearing the device on the lower arm, and one phase wearing the device on their upper arm. The order of the two phases was randomly determined for each participant, and the order was balanced amongst all participants.

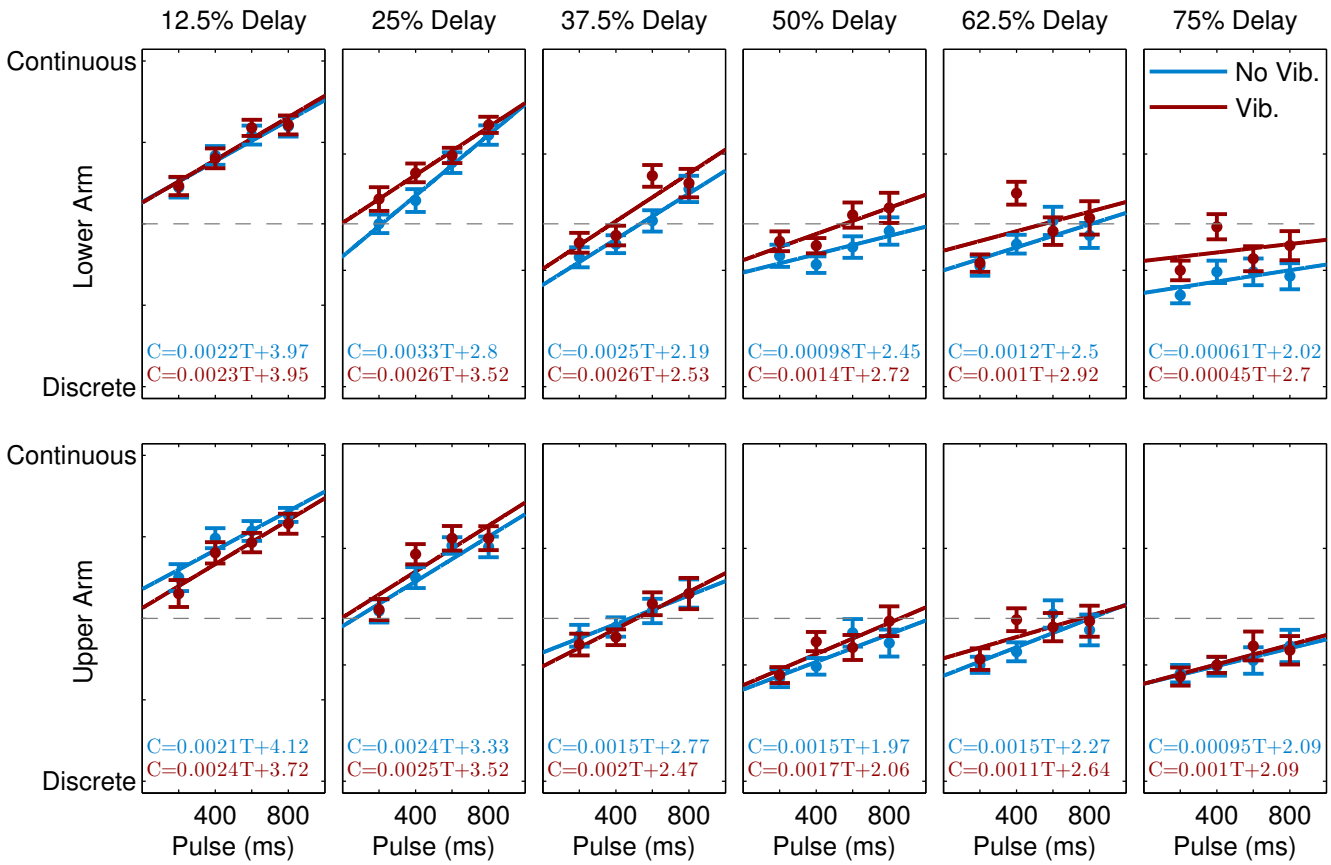

Fig. 7. Average continuity ratings across all participants with standard error bars. Linear regression was done on the average ratings (C is the continuity, T is the pulse width).

In the study, we varied the pulse width (200 ms, 400 ms, 600 ms, 800 ms), amount of delay between actuators (12.5%, 25%, 37.5%, 50%, 62.5%, 75% of pulse width), and the presence or absence of vibration. These parameters resulted in 48 unique actuation conditions, which were repeated twice. The order of conditions was randomized, and participants completed all 96 trials for a device location before switching to the next location. On average, participants completed the study in under 45 minutes.

In the study, participants felt each actuation sequence one at a time. After each sequence, they were asked to rate it on its perceived continuity and pleasantness. Participants rated continuity on a 7-point Likert scale where 1=Discrete and 7=Continuous. They rated pleasantness on a Likert scale ranging from -7 to +7 where negative numbers corresponded to an unpleasant sensation and position numbers corresponded to a pleasant sensation (-7=Very Unpleasant, 0=Neutral, +7=Very Pleasant).

B. Results

Fig. 7 and Table I show the average continuity rating across all subjects, separated by delay and pulse width. We performed a linear regression for the average continuity ratings for each delay value. The positive slopes for all fit regressions indicates that rated continuity increases with pulse width when delay is held constant. Additionally, the continuity decreases with delay, as shown by the combination of generally decreasing intercept values and slopes of the regressions.

We ran a four-way ANOVA on the continuity ratings with arm location, vibration presence, delay, and pulse width as factors. This analysis showed that continuity ratings were statistically higher for the lower arm than the upper arm ($F(1) = 5.57$, $p = 0.018$). Continuity was also significantly lower for the no-vibration condition than when vibration was played ($F(1) = 17.73$, $p = 2.62 \times 10^{-5}$), which shows that playing the vibration does improve the continuity of the sensation.

Continuity was also statistically different for the different delay values ($F(5) = 249.2$, $p = 7.25 \times 10^{-224}$). We ran a post-hoc pairwise comparison test with a Bonferroni correction to further evaluate the effect of delay. Continuity ratings were statistically different for all pairs of delays ($p < 0.001$) except between 50% and 62.5% ($p = 0.25$). Continuity was also significantly different for different pulse widths ($F(3) = 84.7$, $p = 1.24 \times 10^{-52}$). We ran a post-hoc pairwise comparison test with a Bonferroni correct to further evaluate the effect of pulse width. Continuity ratings were statistically different for all pairs of pulse widths ($p < 5 \times 10^{-6}$) except between 600 ms and 800 ms ($p = 0.063$).

TABLE I

AVERAGE CONTINUITY RATINGS

Delay	200 ms	400 ms	600 ms	800 ms
12.5%	4.28 (4.31)	4.97 (4.91)	5.41 (5.56)	5.59 (5.63)
	4.38 (4.03)	5.22 (4.91)	5.38 (5.13)	5.72 (5.53)
25%	3.50 (4.03)	4.00 (4.59)	4.81 (4.69)	5.41 (5.63)
	3.66 (3.69)	4.38 (4.88)	5.06 (5.22)	5.03 (5.22)
37.5%	2.78 (3.09)	3.06 (3.25)	3.56 (4.53)	4.25 (4.38)
	3.13 (2.94)	3.31 (3.09)	3.66 (3.81)	4.03 (4.03)
50%	2.81 (3.13)	2.63 (3.03)	3.00 (3.69)	3.34 (3.84)
	2.22 (2.28)	2.47 (3.00)	3.19 (2.88)	2.97 (3.44)
62.5%	2.59 (2.66)	3.06 (4.16)	3.56 (3.34)	3.25 (3.63)
	2.5 (2.63)	2.78 (3.47)	3.59 (3.31)	3.25 (3.44)
75%	1.97 (2.5)	2.47 (3.44)	2.47 (2.75)	2.37 (3.03)
	2.31 (2.25)	2.47 (2.50)	2.59 (2.91)	2.91 (2.81)

*Values contained within the parenthesis correspond to vibration being applied. The top row for each delay corresponds to the lower arm and the bottom row corresponds to the upper arm.

TABLE II

AVERAGE PLEASANTNESS RATINGS

Delay	200 ms	400 ms	600 ms	800 ms
12.5%	-0.06 (0.19)	1.41 (0.78)	1.84 (1.47)	1.84 (1.19)
	-0.09 (-0.72)	1.22 (0.94)	1.47 (1.72)	2.19 (1.63)
25%	0.69 (-0.16)	1.19 (1.09)	1.63 (1.56)	2.28 (1.31)
	0.94 (0.28)	1.13 (1.34)	1.38 (1.81)	1.09 (1.06)
37.5%	0.09 (0.41)	0.72 (0.41)	0.63 (0.44)	1.16 (0.25)
	1.16 (0.38)	0.84 (0.94)	0.63 (0.84)	1.03 (0.69)
50%	-0.16 (0.25)	0.53 (0.41)	0.31 (0.63)	0.53 (0.06)
	0.22 (0.31)	0.78 (0.66)	0.28 (-0.25)	0.59 (0.81)
62.5%	0.91 (0.34)	-0.13 (0.59)	-0.06 (0.09)	-0.03 (-0.06)
	0.66 (0.25)	0.03 (0.16)	0.16 (-0.09)	0.09 (0.25)
75%	-0.47 (0.0)	0.53 (0.66)	-0.19 (-0.03)	-0.41 (-0.56)
	0.53 (0.06)	0.28 (0.47)	0.09 (-0.41)	-0.84 (-0.91)

*Values contained within the parenthesis correspond to vibration being applied. The top row for each delay corresponds to the lower arm and the bottom row corresponds to the upper arm.

These results show that continuity can be directly controlled by changing the delay between actuators and the duration of an individual actuator pulse.

Fig. 8 and Table II show the average pleasantness rating across all subjects, separated by delay and pulse width. For low delay values (12.5% and 25%), the rated pleasantness increases with pulse width when delay is held constant, as shown by the positive slopes in the linear regressions. However, at high delay values (62.5% and 75%), the rated pleasantness decreases with pulse width, as shown by the negative slopes in the regressions. This decrease in pleasantness was also indicated in post-experiment surveys, where many participants indicated that this high-delay, long-pulse width signals felt like a bug was crawling up their arm and induced a creepy sensation.

We ran a four-way ANOVA on the pleasantness ratings with arm location, vibration presence, delay, and pulse width as factors. This analysis showed that pleasantness ratings were not statistically different based on arm location ($F(1) = 0.22$, $p = 0.64$) or vibration condition ($F(1) = 2.82$, $p = 0.09$).

Pleasantness also statistically different for the different delay values ($F(5) = 20.61$, $p = 2.65 \times 10^{-20}$). We ran a post-hoc pairwise comparison test with a Bonferroni correction to further evaluate the effect of delay. Pleasantness slightly increases from 12.5% to 25% delay, but the change is not significant ($p = 0.99$). Pleasantness then steadily decreased with increasing delay. Across all delay values, the pleasantness ratings were not statistically significant for adjacent delays ($p > 0.05$), but all other comparisons were statistically significant. This shows that pleasantness is strongly linked to actuator delay, but small changes in delay do not have a significant effect.

Pleasantness also statistically different for the different pulse widths ($F(3) = 5.78$, $p = 6.16 \times 10^{-4}$). We ran a post-hoc pairwise comparison test with a Bonferroni correction to further evaluate the effect of pulse width. The pleasantness ratings for 200 ms were significantly lower than the pleasantness ratings of the three higher pulse widths ($p < 0.05$). However, the three highest pulse widths (400 ms, 600 ms, 800 ms) were not statistically different amongst themselves ($p > 0.96$).

We ran one-sample t-tests on the pleasantness ratings grouped by delay value to compare the actual ratings to a neutral rating (Pleasantness = 0). The pleasantness ratings for the four shortest delay values (12.5%, 25%, 37.5%, 50%) were statistically greater than zero ($p < 2 \times 10^{-4}$), which indicates that these conditions were on average rated as pleasant. The pleasantness ratings for the two longest delay values (62.5%, 75%) were not statistically greater than zero ($p > 0.05$). None of the delay values were rated as statistically less than zero (unpleasant).

We also ran one-sample t-tests on the pleasantness ratings grouped by pulse-width values to compare the actual ratings to a neutral rating. The pleasantness ratings for all pulse-width values (200 ms, 400 ms, 600 ms, 800 ms) were statistically greater than zero ($p < 9 \times 10^{-4}$), which shows that all pulse widths were on average rated as pleasant.

C. Discussion

The results of this study indicated that the perceived continuity of the stroke sensation increases with pulse width and decreases with delay. These observed trends were consistent across all of the tested actuation parameters. The results also indicated that the pleasantness of the interaction is highest for short delays and increases with pulse width for these values. This correlation between continuity and pleasantness was also seen with vibration illusory motion [23]. Therefore, to create a continuous and pleasant sensation, the device should be controlled with a short delay and long pulse width. The signal that was rated highest for continuity was the same as the signal rated highest for pleasantness (800 ms, 12.5% delay). Interestingly, the effective speed of travel of the sensation up the arm for this signal was 13.5 cm/s, which, although slightly above the optimal range for activating the CT afferents, was the slowest speed tested that was perceived as pleasant. Although slower illusory strokes were tested, these were reported to be unpleasant and creepy due to the combination of delay and pulse width necessary to achieve

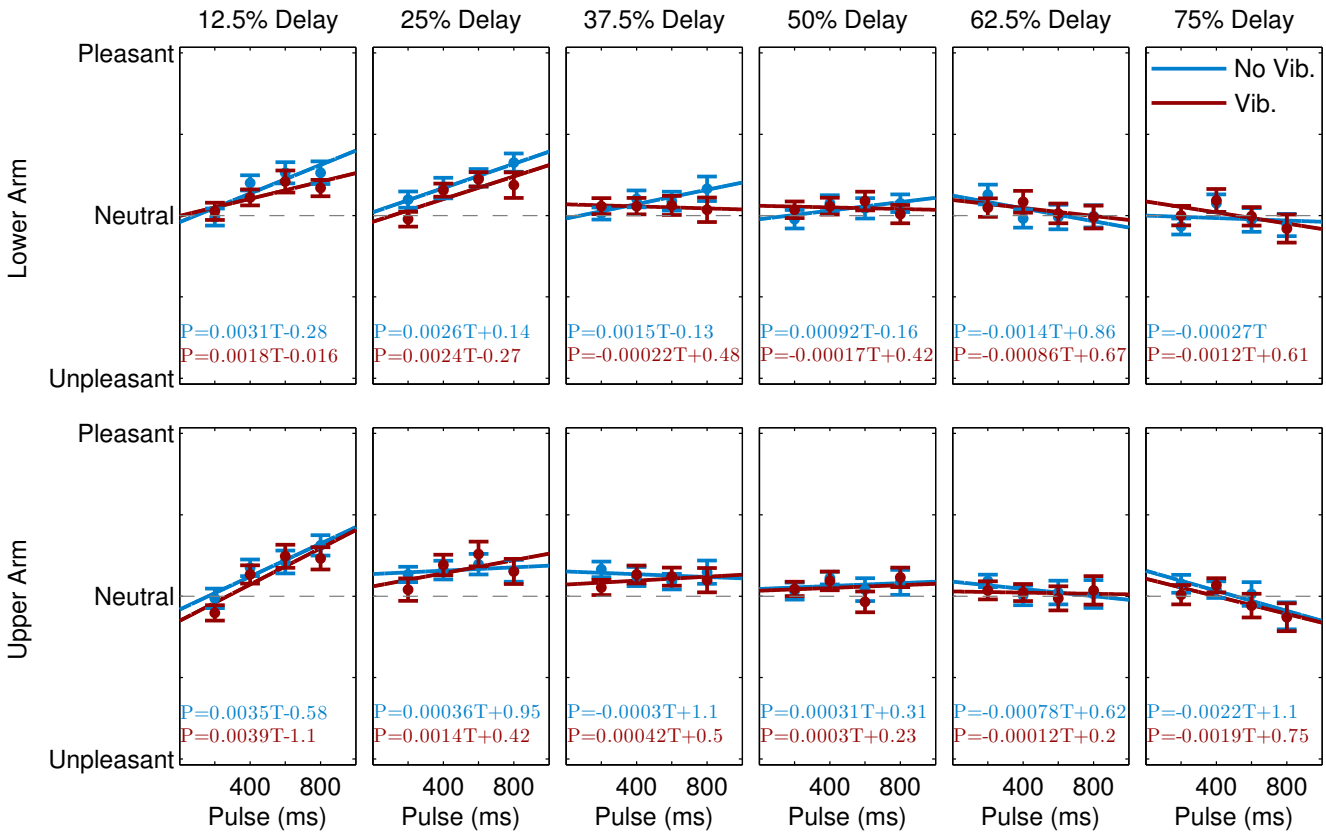

Fig. 8. Average pleasantness ratings across all participants with standard error bars. Linear regression was done on the average ratings (P is the pleasantness, T is the pulse width).

the lower speeds.

While lateral stroking motion has been shown to be particularly effective at stimulating the CT afferents, they have also been shown to respond to normal indentation in the range of frequencies tested here [19]. More research is needed to determine the role of the CT afferents in the perception of the illusory motion created with this device.

The added vibration had a positive effect on continuity, but did not significantly affect the perceived pleasantness of the signals. This result proves the effectiveness of our vibration scaling scheme for creating tactile flow and also supports our decision to use data-driven vibrations rather than simple sinusoidal vibrations. Since the vibrations had only a positive effect on our metrics, they should be included as part of the actuation.

Participants rated the signals as more continuous when felt on their lower arm than on their upper arm. However, there was no difference in pleasantness between the two arm locations. One possible explanation for this discrepancy could be that the contact between the tactors and skin was not consistent at the different arm locations due to variations in arm shape. A second possible explanation could be differences in the perception of the lower and upper arms. The CT afferents have been studied extensively in the lower arm, but not much is known about their response to stimuli in the upper arm [5]. In terms of wearability, participants did not express a preference for wearing the sleeve on their lower or upper arm, but a sleeve on the upper arm might be less obtrusive and easier to conceal under clothing if the device were to be worn in everyday life.

Although the average ratings for pleasantness were low, the illusory motion generated by this device was shown to be pleasant when driven with certain actuation parameters. This shows promise for our device because, at a minimum, social haptic devices should create sensations that are perceived as either neutral or pleasant (i.e., not unpleasant). Furthermore, the study showed that choosing the correct set of actuation parameters is key to creating pleasant sensation with this device. It was easy to create an unpleasant and even creepy sensation by choosing non-optimal combinations of delay and pulse width.

The present results provide parametric models for rendering lateral sensations on the arm using normal indentations. These sensations create artificial touch gestures that could resemble to strokes, pats, and rubs, all of which are critical for touch interactions between individuals who are physically apart. Previous research had developed similar models for vibrations [22], [23] that were perceived as 'synthetic'. The present work gives us the ability to render realistic feelings, in an effort to enhance social presence for remote communication and while in VR and VE settings.

IV. Conclusions and Future Work

We presented the design and evaluation for a device that creates a stroking sensation on the arm using sequential indentation of the skin. The device is comprised of a linear array of voice coils that is worn in a sleeve on the arm. The voice coils are controlled to indent the skin in a linear pattern to create the sensation of a stroking motion even though only normal force is applied. We evaluated the device with a human-subject study and determined that each individual indentation should have a long pulse width (800 ms) and there should be a short delay between the start of indentation for adjacent actuators (12.5% of pulse width) in order to maximize both the perceived continuity and pleasantness of the interaction. In future work, we will model the interaction to determine the optimal spacing and placement of the actuators.

This device could be used for social haptic applications or extended to information transfer or navigation applications. The study in this paper showed that a sensation of lateral flow can be generated using only normal force. This result has important implications for actuator design and selection because it is important to minimize the number of degrees of freedom of actuation in order to maximize wearability. In addition, in future work we will examine other haptic device designs based on the described sketches.

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