PixeLite: A Thin and Wearable High Bandwidth Electroadhesive Haptic Array

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***Abstract*—We present PixeLite, a novel haptic device that produces distributed lateral forces on the fingerpad. PixeLite is 0.15 mm thick, weighs 1.00 g, and consists of a 4×4 array of electroadhesive brakes ("pucks") that are each 1.5 mm in diameter and spaced 2.5 mm apart. The array is worn on the fingertip and slid across an electrically grounded countersurface. It can produce perceivable excitation up to 500 Hz. When a puck is activated at 150 V at 5 Hz, friction variation against the countersurface causes displacements of 627 ± 59 μm. The displacement amplitude decreases as frequency increases, and at 150 Hz is 47 ± 6 μm. The stiffness of the finger, however, causes a substantial amount of mechanical puck-to-puck coupling, which limits the ability of the array to create spatially localized and distributed effects. A first psychophysical experiment showed that PixeLite's sensations can be localized to an area of about 30% of the total array area. A second experiment, however, showed that exciting neighboring pucks out of phase with one another in a checkerboard pattern did not generate perceived relative motion. Instead, mechanical coupling dominates the motion, resulting in a single frequency felt by the bulk of the finger.**

***Index Terms*—Soft wearable haptics, electroadhesion, lateral skin stretch, distributed forces, texture perception.**

I. Introduction

No EXISTING tactile display can create a realistic sense of touching a natural texture, such as fabric. Achieving realism in virtual touch is a daunting challenge due to the complex mechanics of skin-surface interaction and the spatiotemporal coding of touch [1], [2], [3], [4]. Good progress has been made in both recording and displaying textures via hand-held stylus devices [5], [6], [7], but the case of bare fingertips has proven to be much more difficult [2], [3]. Even with fine textures (i.e., length scales <200 μm), where it is known that skin vibrations elicited from tactile exploration are texture-specific [1], [2], playback of those vibrations is not sufficient to match real and virtual textures [3].

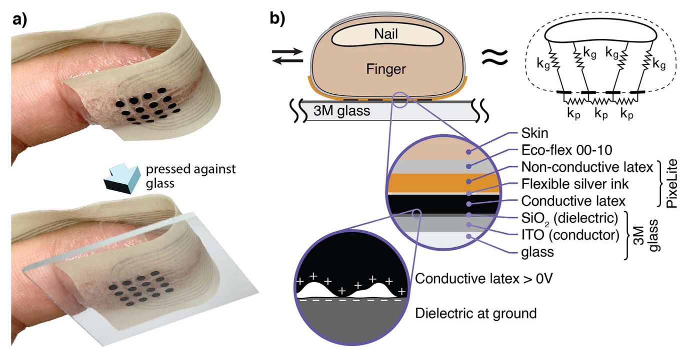

Fig. 1. (a) PixeLite worn on a finger with a 50 μm layer of Ecoflex 00-10 and pressed against a glass. (b) A cross-sectional view of PixeLite worn on the finger and interacting with a 3 M glass, its layer stack up, and a predicted linear elastic model.

Recently, a pin array was used to show that millimeter-scale spatial patterns strongly influence perception even at fairly high frequencies (e.g. 80 Hz) [8]. When all pins were vibrated at identical amplitude and frequency, but separated into two groups by phase, roughness perception was directly proportional to the phase difference. This suggests that to recreate realistic fine textures, it may be necessary to produce high bandwidth, spatially distributed excitation.

Distributed stimulation within the fingerpad has been achieved with array-based devices, but primarily for shape-recognition tasks [9], [10], [11]. Many such devices actuate the fingerpad in the surface-normal direction and do not apply any of the lateral tractions that are associated with swiping a finger over a texture. Additionally, many devices involve large, rigid components that make it hard to mimic natural texture exploration motions. Smaller, more easily moveable devices typically have bandwidth limitations and cannot achieve the vibrations needed for fine texture replication. In contrast, surface haptic devices based on modulating friction via electroadhesion can achieve high bandwidth [12] but do not offer spatial distribution.

To provide a pathway toward high realism texture display, we have developed a high bandwidth, array-based electroadhesive device that produces spatially distributed lateral tractions on the

Manuscript received 16 December 2022; revised 19 March 2023; accepted 13 April 2023. Date of publication 3 May 2023; date of current version 19 December 2023. This work was supported in part by the National Science Foundation under Grant 2106191, in part by the NUFAB facility of Northwestern University's NUANCE Centerthrough SHyNE Resource under Grant NSF ECCS-2025633, in part by the IIN and in part by Northwestern's MRSEC Program under Grant NSF DMR-1720139. This paper was recommended for publication by Associate Editor K.-U. Kyung and Editor-in-Chief S. Choi upon evaluation of the reviewers' comments. *(Corresponding author: Sylvia Tan.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Northwestern University Institutional Review Board, STU00215089, performed in line with The Belmont Report.

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Digital Object Identifier 10.1109/TOH.2023.3272635

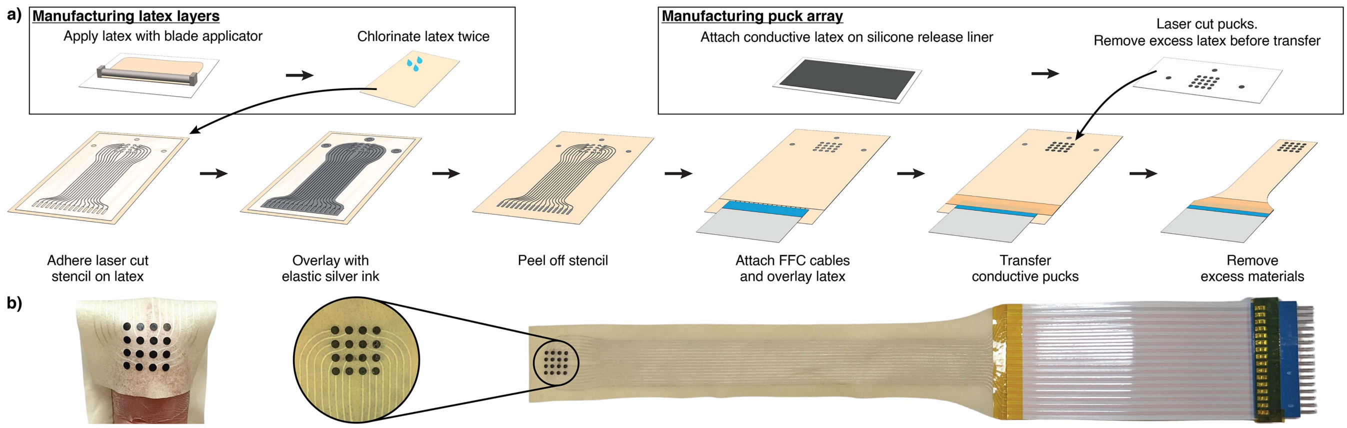

Fig. 2. A layering fabrication process was developed to allow for quick design iterations. (a) The full fabrication process of making a 4×4 PixeLite. (b) Close-up and full picture of the device. The pucks are 1.5 mm in diameter, 2.5 mm center-to-center, and 0.15 mm thick.

fingerpad. This device, which we call "PixeLite," is thin, flexible, and wearable. It conforms to the finger, allowing the user to freely explore a physical surface. Electroadhesive friction modulation between individual pucks and the surface (an electrically grounded conductive plane covered by a thin insulator) produces distributed stimulation. PixeLite produces lateral motions, which are known to be effective in conveying information to the fingerpad [13], [14], [15]; moreover, at smaller displacements, subjects are unable to distinguish between normal and lateral displacements [16]. Nonetheless, a central research question is whether distributed lateral tractions will be sufficient to convey texture sensations on the fingerpad, or whether normal displacements are also needed.

II. PixeLite Design

PixeLite consists of a 4×4 array of individually controlled electroadhesive "pucks" (Fig. 1(a)) 1.5 mm in diameter spaced 2.5 mm apart. It has a total thickness of 0.15 mm and weighs 1.00 g (not including FFC cable). For wearability, the finger is wrapped with a 50 μm layer of silicone rubber, Ecoflex^{TM} 00-10, to which PixeLite is then attached. Ecoflex 00-10 was chosen for its tacky surface, which acts as a soft adhesive layer, and because it has a significantly lower modulus than skin (800% elongation at break [17]), is flexible enough not to interfere with the pucks' motions. To actuate the pucks, the user moves over a grounded 3 M MicroTouch^{TM} glass, and an AC signal can be sent to each puck. At high voltage, the electrostatic attraction between the puck and glass causes an increase in frictional force, which can be perceived by the user (Fig. 1(b)). With a 150 V square wave input, the pucks are tactically perceptible up to 500 Hz.

III. Fabrication

A. Materials

Initial tests were performed with various materials (PVDF, Aluminum oxide, and conductive latex) contacting an electrically grounded 3 M glass to determine which could produce perceptible tactile sensations and be readily fabricated into a lateral-only haptic device. At a given voltage, a weakly conductive latex (ESDFC-B-5, Bertech) produced the highest frictional forces perceived by the lead author. Adding a soft layer above the latex further improved the effect. We hypothesize that the soft layer allows for the additional compression of the conductive latex, increasing the true contact area, and leading to higher electroadhesion forces. This is further emphasized when testing with electrical leads of varying flexibility (magnet wires, copper film, and elastic conductive ink). Consistent with the hypothesis, the elastic conductive ink (118-43(LPS), Creative Materials) resulted in the highest frictional force, presumably because it preserved the latex's elasticity.

B. Fabrication Process

Our fabrication process is illustrated in Fig. 2(a). Thin, soft components were used to ensure that the pucks did not pre-indent the fingerpad perceptibly (the intent was to stimulate the skin with exclusively lateral tractions). All layers were constructed from 70 μm thick sheets of non-conductive or conductive latex made with an automatic applicator (TQC Automatic Film Applicator, Industrial Physics). The sheets were chlorinated twice after curing to reduce the material's friction coefficient. To make the latex conductive, 1 wt% carbon nanotubes (Tuball latex, OCSiAl) was mixed into the latex with an overhead stirrer for 15 minutes at 150 rpm prior to application. The electrical leads were made with flexible silver ink applied directly onto the non-conductive latex with a stencil cut from a 76.2 μm sheet of polyester film. All other layers were glued together with a permanent spray adhesive (Super 77^{TM}, 3 M) to prevent any built-up of rigid adhesive materials.

IV. Characterization

The device was characterized with the tribometer originally developed by Grigorii et al. [3]. The normal force and scan speed were fixed at 0.8 N and 20 mm/s respectively, and the finger incidence angle was adjusted such that the array was parallel to the grounded countersurface (3 M glass). Bulk finger vibrations were measured with a Laser Doppler Vibrometer (LDV). An additional camera and lighting were added to the tribometer to record the puck's motions under the stationary

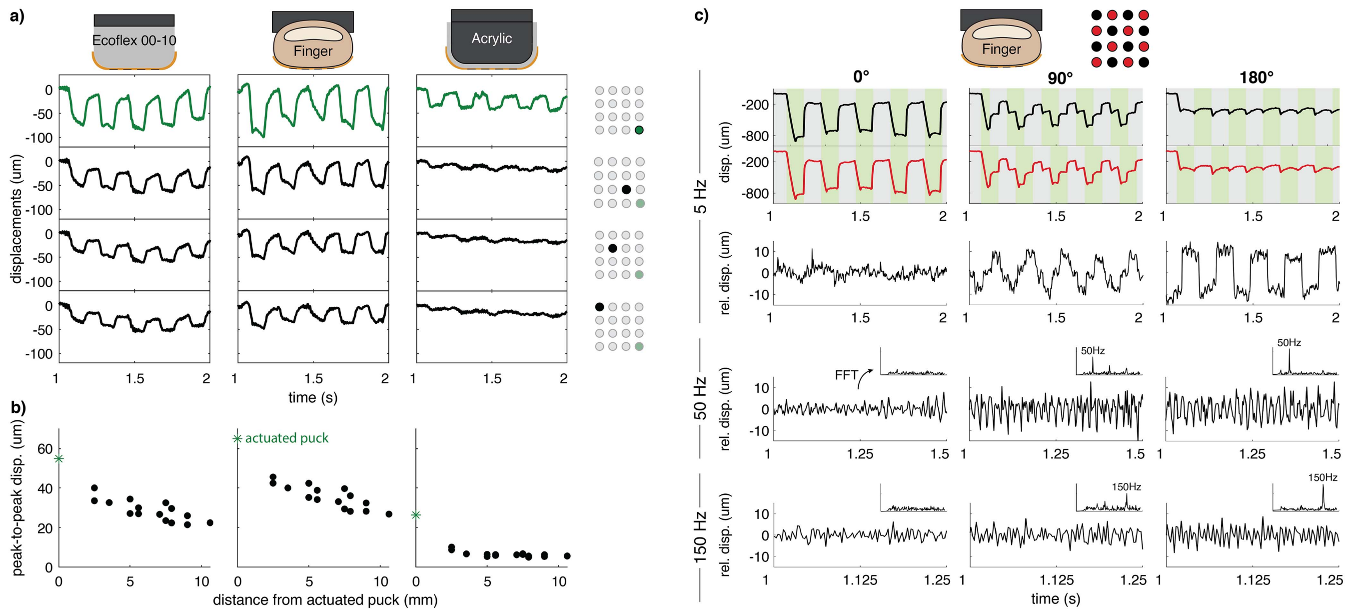

Fig. 3. Behavior of PixeLite when using a soft finger analog (Ecoflex 00-10), a real finger, and a rigid finger analog (acrylic). When only actuating a single puck in the bottom right corner (green), (a) displacements of pucks with increasing distance from the actuated puck and, (b) peak-to-peak displacements of all pucks versus distance from the actuated puck. (c) Behavior of the device on a real finger at three frequencies (5, 50, 150 Hz) when all pucks are actuated in a checkerboard pattern and only phase delay between alternating pucks is changed. The black and red displacement lines are the average displacements for the black and red pucks respectively, and the relative displacements are the differences between the two groups.

glass, and motion analyses were performed with the same image processing method as Tan et al. [15].

A. Independent Motion

A key requirement of the design is that pucks can move relative to one another. An initial concern was that the stiffness of the base latex layer would couple the pucks to one another. To test this, two simplified versions including only two pucks were made, one with the base latex connecting the pucks, and another with them mechanically disconnected (device cut in half). The device was attached to a real finger and one puck was grounded while the other was actuated at 5 Hz and 150 V. Their motions were recorded at 1280 × 960 px, 296 fps. We observed that regardless of the device's configuration, both pucks moved together. The grounded puck displaced less, but its motion was coupled to the actuated puck.

Following this, the effect of the finger's stiffness was explored. The full device (4×4 array) was placed on a real finger, a soft finger analog, and a rigid finger analog. The rigid finger was made of acrylic (∼ 3.17 GPa), and the soft finger was made of Ecoflex 00-10 (0.05 MPa). For the rigid finger, an additional 1250 μm layer of Ecoflex 00-10 was added between the acrylic and the device to allow some degree of puck motion. Only the bottom right corner puck was actuated with 180 V at 5 Hz, while all other pucks were grounded.

Fig. 3(a) shows the displacements of 4 selected pucks, each subsequent row at increasing distance from the actuated puck (top row). For the real finger, the actuated puck had an average peak-to-peak displacement (Δx) of 65 μm, and the vibrations propagated to all other pucks, where the amplitude decreased as the distance from the actuated puck increased (Fig. 3(b)). At the greatest distance (10.6 mm), the puck's average Δx was 29 μm. Additionally, the effect of propagation was stronger in the direction of motion. Similar trends were seen for the soft finger. The slight decrease in overall motions when compared to the real finger was attributed to variations that occurred when calibrating the device, rather than the differences in the mechanical properties of the fingers. In contrast, the rigid finger had a minimal propagation effect, but the actuated puck's amplitude was less than half of that of the real finger. This result is in line with the predictions of a simple linear elastic model (Fig. 1(b)): the amount of relative displacements between an actuated puck and any other puck depends on the ratio of the stiffness coupling each puck to ground (k_g), to the stiffness coupling the two pucks (k_p). The greater k_g/k_p, the greater the relative displacements; additionally, a greater k_g reduces the overall motion amplitude. For the human finger, the Stratum Corneum (k_p) is much stiffer than all the inner tissue (k_g) [18], resulting in a small k_g/k_p and leading to a strong propagation of motion.

B. Phase Effect

We explored the effect of varying phases between adjacent pucks, with all the pucks excited at a given frequency. PixeLite was worn on a real finger and all pucks were actuated at 150 V while the phase delay between every other puck in a checkerboard pattern was set to 0, 45, 90, 135, and 180 degrees. This was tested at 5, 50, and 150 Hz. The camera recorded the pucks' motions at 1280 × 720 px, 389.6 fps.

Due to the mechanical coupling of the pucks through the finger, all pucks followed the same motion pattern of the superposition of the two signals (Fig. 3(c)). At 5 Hz, the largest

Δx occurred at 0° with 627 ± 59 μm, and no relative displacements between the two groups of pucks were seen as expected. Δx decreased as the phase increased, and at 180° phase delay, the pucks were displaced by 140 ± 13 μm, and had relative displacements of 22 ± 3 μm at 5 Hz between adjacent pucks.

However, at 50 and 150 Hz, different phase delays and Δx relationships were observed. At 50 Hz, Δx at 0° was 188 ± 12 μm and Δx peaked at 45° with 222 ± 7 μm. This remained consistent at 90° and decreased slightly to 164 ± 20 μm at 135°. It dropped sharply at 180° to 35 ± 10 μm. Relative displacements at 50 Hz were observed at phases above 0°, and the largest difference achieved was at 180° with 14 ± 3 μm. At 150 Hz, Δx remained constant between 0° and 90° at 47 ± 6 μm, and decreased after, reaching 17 ± 4 μm at 180°. Similar to 50 Hz, the largest relative displacements happened at 180° with 8 ± 2 μm. Thus, it is apparent that PixeLite succeeds in producing relative displacements within the array; yet, these displacements are small, both in absolute amplitude and relative to the common displacement (the largest relative displacement achieved was 46.7% of the common displacement).

Bulk finger vibrations recorded with the LDV also showed that the fundamental finger vibration frequency occurred at the actuation frequency. The vibration strength decreased as the phase delay increased, and at a 180° phase delay, the dominant vibration occurred at twice the actuation frequency.

V. Psychophysical Experiments

In a first experiment, participants were asked to identify which individual puck was being actuated while all others were grounded. In a second experiment, users provided roughness ratings for stimuli where adjacent pucks were actuated at varying phase delays.

The previously mentioned tribometer was used in both studies, and the subject's dominant index finger was swiped across a 3 M glass at 20 mm/s for 2 seconds. The puck(s) were actuated for 1 s after the first 0.5 s to ensure the finger had fully slipped before they were turned on. The normal force was fixed at 0.8 N, and the finger incidence angle was adjusted for each user such that the full array was parallel to the countersurface. An initial calibration of the device was performed for each subject, where each puck was vibrated at 50 Hz and the subject verbally indicated if they could feel the vibration and if the vibration strength was similar for all pucks. Subjects also wore headphones playing pink noise to disguise any sounds produced by the apparatus. Twelve subjects (aged 25.25 ± 3 years, 4 females) participated in the experiments. Subject participation was approved by the Northwestern Institutional Review Board, and subjects were paid for their time.

A. Experiment 1

Before the test, subjects were familiarized with the layout of the array on their finger. All 16 pucks were actuated successively, and subjects were informed which puck was actuated before it happened. They then completed a training session where a random puck was actuated and they had to identify it; correct feedback was provided after the response. They repeated the training 32 times, going through the full array twice. In the test, 8 pucks were selected from three regions of the array: corners, sides, and middle. The experiment consisted of 24 trials, 3 for each puck, and was randomly ordered (Fig. 4(a)). In both the training and test, subjects could replay each stimulus until they felt confident of an answer.

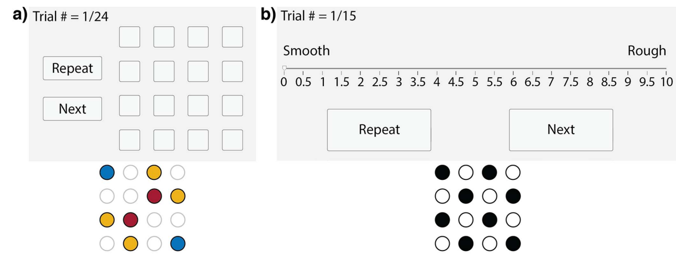

Fig. 4. (a) GUI interface of experiment 1 and pucks tested grouped by color (each representing a different accuracy level). (b) GUI interface of experiment 2 and the two groups of pucks used in varying phases (white vs black pucks).

B. Experiment 2

In the same setup configuration as experiment 1, participants gave roughness ratings (0 = smooth to 10 = rough) to actuation patterns varying in frequency and phase delay. A given pattern actuated all the pucks at 150 V, at one of three frequencies (50, 150, or 250 Hz), and the two interspersed subsets of pucks were activated with one of five phase delays (0, 45, 90, 135, or 180°) (Fig. 4(b)). Each actuation frequency was tested in a single block, with the 5 phase conditions tested three times, in random order. Before a block, subjects familiarized themselves with the 5 phase conditions being tested. A bit of reflective tape was added to the side of the finger so that an LDV could record the bulk finger vibration for every trial.

VI. Results

A. Experiment 1

A grid map of the array was made with the bottom left corner puck set as the origin and the inter-puck spacing set as one unit. All tested pucks and subject responses were given xy-coordinates based on the grid map. For each tested puck, the spatial centroid of each subject's 3 responses was calculated with the given xy-coordinates, and plotted as point clouds in Fig. 5(a). Using the 12 spatial centroids (one for each subject), a standard deviation ellipse (SDE) was calculated for each tested puck. The center of the ellipse was the xy mean of the 12 points, and the standard deviation and angle of rotation were calculated using the deviations of the 12 points from the mean center. The average ratio between the area of the SDEs to the area of the array was 0.402 ± 0.103. Within a subject, SDEs were also calculated with the 3 responses for each tested puck, and the angle of rotation of the ellipses did not suggest a directional bias (left-right, top-down).

To measure error for each tested puck, spatial weight matrices were first created, representing the weight from the tested puck

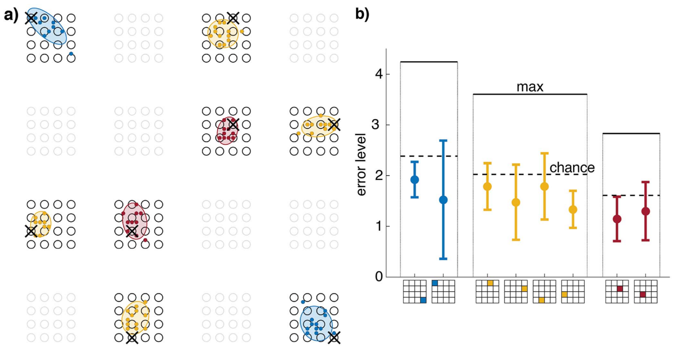

Fig. 5. Results of identifying singular pucks on the array, (a) point cloud of each subject's spatial mean for a given actuated puck and the resulting overall SDE. (b) The error level of each actuated puck and their maximum possible and chance values (colors indicate puck locations: blue = corner, yellow = edge, red = center).

to all potential response pucks. The weight from the tested puck to a response puck was the unit distance between the two. For each subject, the error level for each tested puck was computed as the sum, across all response pucks, of the weight to a response puck multiplied by the number of times it was given as a response. The results can be seen in Fig. 5(b). A Monte Carlo test was run with 1000 samples to determine chance levels for each puck. The means for all tested pucks fell below the 95% confidence interval, indicating a significant deviation between mean response locations and chance.

B. Experiment 2

For each frequency, each subject's roughness ratings were scaled to 0 - 1 (Fig. 6(a)). Subjects consistently reported minimum roughness at the 180° phase delay for all frequencies. Otherwise, the frequencies differed in the extent to which roughness varied monotonically with phase delay. In particular, there was a clear peak at 90° for 50 Hz. At 250 Hz, a linearly decreasing relationship between roughness rating and phase delay was found.

Because it has been shown that bulk finger vibrations correlate strongly with the perception of the roughness of fine textures [19], [20], an analysis of the LDV recordings was also performed. A high-pass filter was applied to the raw LDV recordings to remove the finger DC motion, and spectral subtraction noise reduction was performed using the first and last 0.5 s of the recording (when no signals were being sent to the pucks). A Fourier analysis was then performed on the noise-reduced signal, and the power of each component of the Fourier transform was divided by the threshold amplitude at the respective frequency extrapolated from Bolanowski et al. [21] (only frequencies between 0 - 500 Hz were included). Following Bensmaia (2005), the effective intensity of a stimulus was obtained by:

$$I_s = \sum_f P_s(f)^{a_f} \quad (1)$$

where P_s was the threshold-weighted power of the spectral component at frequency f, and a_f was inter- and extrapolated from Bensmaia et al. [22] best-fit values that account for the difference in effective to objective intensity across f. The effective intensity for each subject was normalized across all the recordings at each frequency (Fig. 6(b)). The effective intensity tended to co-vary with the perceived roughness, such that the effective intensity had decreasing trends as phase delay increased, and similar peaks between roughness ratings and effective intensities were seen for 50 and 150 Hz. Across all frequencies, 180° phase delay consistently resulted in the lowest bulk finger vibration amplitudes, consistent with the lowest roughness level found there.

The relationship between roughness perception and bulk finger vibration can be seen in Fig. 6. At all frequencies, a direct correspondence between the mean roughness rating and mean effective intensity can be seen. For 250 Hz, phase delay also correlates strongly with both. We also note that the large inter-subject variability at 50 and 150 Hz leads to greater inter-subject variability in the relationship between roughness and vibration.

VII. Discussion

A. Experiment 1

As seen in Fig. 5(a), participants were able to localize the position of a single actuated puck. The SDEs had average axes of 2.66 ± 1.56 mm, showing that the array is able to provide spatial information, but only with center-to-center distances larger than 5 mm.

The limited spatial discrimination is likely due to the mechanical coupling of the pucks through the finger. As seen in Fig. 3(b), despite only actuating one puck, all adjacent pucks vibrated at the same frequency with slightly diminishing amplitudes. When the pucks are furthest away from each other (corner-to-corner), the actuated puck is displaced 2.43 times more, allowing the participants to make a reliable judgment. This can be seen where only 37.5% of the bottom right corner puck's SDE overlapped with the top left corner puck's SDE. In comparison, an actuated puck displaces only 1.43 times more than its adjacent puck. This smaller difference resulted in participants having a lower ability to distinguish neighboring pucks, and 85.7% of the middle right SDE overlapped with the middle left puck's SDE.

B. Experiment 2

From Fig. 6, it can be seen that the bulk finger vibration played a significant role in influencing subjects' roughness perception. This can be attributed to the large common motions of the pucks and the small relative motions between them. Although the relative motions enabled the array to provide some spatial information for experiment 1, when all 16 pucks were actuated, the common motion was significantly larger than the achievable relative displacements between neighboring pucks. At all frequencies, the largest relative displacements were achieved at 180°, but at 50 and 150 Hz, they were only 39.4% and 46.7% of the overall puck motion respectively. At lower phase delays, the ratios between relative displacement and the overall motion were all below 10% for 50 Hz, and below 30% for 150 Hz. As such, the common motions of the pucks were found to be directly correlated to the bulk finger vibration, and the peaks in the roughness ratings and effective intensity of the stimulus

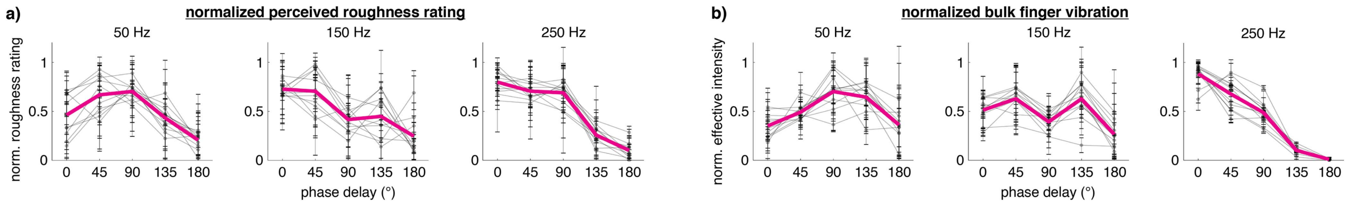

Fig. 6. At the 3 actuation frequencies (50, 150, 250 Hz), (a) each subject's normalized roughness rating versus the phase delay between pucks, and (b) each subject's normalized bulk finger vibration effective intensity versus the phase delay between pucks. Red lines show the mean normalised rating and effective intensity.

were caused by the harmonics from the superposition of the two signals (one for each group of pucks in the checkerboard pattern).

As seen from Fig. 3, when the phase increased, the pucks' movements followed the superposition of the two signals. This resulted in an amplification of the third harmonic. The amplification is highest at 90° phase delay. At 50 Hz, the third harmonic is 150 Hz and is strongly perceptible, causing the peak in both roughness perception and effective intensities. While for 150 and 250 Hz, the third harmonics are 450 and 750 Hz respectively. 750 Hz is outside the perceptual range and is thus not accounted for in the effective intensity. While 450 Hz can be perceived, $a_{f,450}$ is smaller than $a_{f,150}$ and significantly reduces the effective intensity at 450 Hz.

VIII. Conclusion

We developed PixeLite, a flexible and wearable device that provides spatial and temporal distribution of lateral forces on the fingerpad. With a weight of only 1.00 g and thickness of only 0.15 mm, the user can freely explore a surface with no constraints. Each puck in the array is individually actuated and is tactically perceptible up to 500 Hz. With a 150 V - 50 Hz signal, the pucks have a peak-to-peak displacement of 222 ± 7 μm. A novel multi-layered fabrication process was also developed using only soft, stretchable materials.

Physical characterization and psychophysical studies suggest that the stiffness of the finger mechanically couples the pucks together, creating large common peak-to-peak displacements and small relative displacements. Although this was sufficient for creating perceptually isolated regions on the finger, fine texture requires higher spatial resolution. Future work aims to increase the resolution by including normal motion that can overcome the finger's stiffness.

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