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A Soft Wearable Tactile Device Using Lateral Skin Stretch

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***Abstract*—This paper presents an initial study of a soft wearable tactile device that stimulates the finger pad via lateral forces. The device is wrapped around the finger and consists of a 4 × 4 array of pucks with a 2.6 mm pitch. Users interact with a magnet that achieves displacements of ± 56 µm. Two psychophysical experiments were conducted to explore the utility of the device. They showed that the lateral forces obtained were sufficient for the perception of angled lines, and the array-based system provided repeatable edge detection.**

I. INTRODUCTION

Techniques such as ultrasonic vibration [1] or electroadhesion [2] that modulate the friction forces between a fingertip and surface are used in surface haptic devices and can successfully reproduce tactile sensations [3, 4]. However, these approaches are often limited. They operate uniformly over the entire finger pad and cannot reproduce sensations induced by textures that apply significant spatially distributed shear and normal forces. Lederman and Klatzky [5] established that while surface roughness estimation and vibrotactile sensation can both be achieved without access to spatially distributed haptic information, such cues play an important role in geometric tasks such as identifying the 2D orientation of surface features. It was further established that when interacting with virtual objects, an ideal spatial resolution of one transducer per mm^2 is required to replicate recognizable shapes through haptic stimuli [6]. Additionally, a large coverage area of the fingertip is necessary to improve shape recognition [7].

As such, researchers have developed two-dimensional array tactile displays consisting of stimulators that can independently indent into the finger pad. Electric motors [8, 9, 10], pneumatic actuators [7], piezoelectric actuators [11, 12], shape memory alloys [13], solenoids [14], and others have been employed for stimulation. However, the actuators are often bulky and become a limiting factor when trying to reach either the necessary spatial resolution or fingertip coverage area. Additionally, their rigidity makes it difficult to translate the actuation technique into a wearable device.

Aside from normal stresses, shear stresses are also known to induce a variety of tactile sensations. Hayward and Cruz-Hernandez [15] suggested that lateral movement on the order of ± 50 µm is sufficient for sensation intelligibility, and Gaffary et al. [16] showed that participants were able to perceive and recognize letters (80 – 97%) using only skin

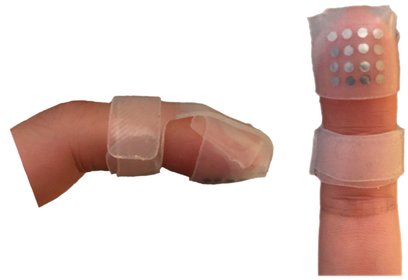

Figure 1. Side and front view of the soft wearable device worn on the finger.

stretch information. Pasquero and Hayward [17] further introduced STReSS, a high-density lateral skin stretch array using piezoelectric combs, and fulfilled the 1 transducer/ mm^2 spatial resolution. A second iteration, STReSS^2 [18] optimized the distribution of the transducers on the fingertip and covered an active surface of around 100 mm^2. It produced a deflection of 0.1 mm and had a bandwidth above 250 Hz. However, it was designed as a tabletop device and its actuation method is not conducive for a wearable.

This paper proposes a novel soft wearable tactile device that wraps around the fingertip and stimulates the finger pad laterally. Inspired by surface haptics, the concept is to control lateral forces between an array of pucks stuck to the finger and an underlying surface. To achieve the high spatial density, compactness, and high bandwidth, pucks actuated by electroadhesion will eventually be used. However, to explore the perceptual utility of the approach, an initial study was performed based on ferromagnetism.

II. DESIGN AND FABRICATION

The design of the soft wearable tactile device consists of a 4 × 4 array of steel pucks attached to the finger pad (fig. 1). The pucks are attracted to a static magnet under a non-magnetic plate as the user slides their wrapped finger across, causing the pucks to move laterally. The device was fabricated using a layer molding process whereby the pucks were embedded in silicon rubber, Ecoflex^{TM} 00-10, within a 3D printed mold. The pucks are punched from a 0.076 mm thick steel shim, measure 1.8 mm in diameter, and are arranged with a center-to-center distance of 2.6 mm.

The total thickness of the device is 0.9 mm; the layer-stack up can be seen in figure 2. Ecoflex 00-10 was chosen as the base material as it is extremely stretchable (800% elongation at break [19]) and thus allowed the maximum movements of the pucks. A thicker layer was placed between the pucks and interacting surface to reduce the probability of the pucks being detached from the device when they were attracted to the magnet, whereas a thinner layer was used between the finger pad and pucks to ensure any movements of the pucks would be transmitted to the skin.

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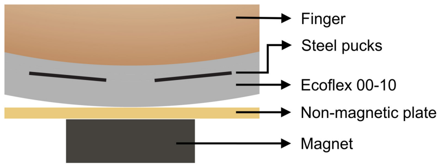

Figure 2. Layer stack up of the finger and device interacting with a magnet.

The base material's flexibility also allowed the device to be easily wrapped around the fingertip and conform to various finger sizes. As it has a tacky surface, no additional adhesive was required to attach it to the finger. However, to reduce friction between the device and the non-magnetic plate, talc powder was applied to the outer interacting with the non-magnetic plate. A new device was worn after each use to enhance adhesion and maximize and control the puck's interaction with the surface and finger pad.

III. Lateral Movement Analysis

The interaction between the pucks and magnet was assessed by examining video footage of the soft wearable tactile device as it slid over a static bar magnet under a brass plate (fig. 3). To view the behavior of the pucks, a piece of molded SORTA-Clear^{TM} 37, mixed in an A:B weight ratio of 2:1, was used as a transparent finger analog. The analog finger was leveled and preloaded by 0.98N to mimic the average force applied during sliding exploration on touch screens [20]. It was moved manually at either approximately 8 mm/s or 3 mm/s, and the pucks' movements were recorded above with a Logitech C290 camera at 30 fps. All measurements and analysis were done in Matlab.

The camera resolution and image magnification were such that one pixel corresponded to 37.1 ± 0.5 μm at the interface between the wearable device and the non-magnetic surface. Each frame was analyzed using a Canny edge detector to produce a binary mask containing the boundary pixels of each puck. Due to optical variations within the finger analog, this did not always yield closed continuous edges, and generated some undesired artifacts. A dilation operation on the binary mask was used to join near-adjacent edge fragments, which were then filled with a convex hull operation. The size distortion due to the image dilation was reversed using a binary erosion, and the resulting blobs were filtered by size to remove unwanted artifacts. Pixels in the original Canny edge mask that also appeared on the edge of one of the final sets of blobs were considered to be true puck edge pixels. A circular regression was then applied to each puck's set of edge pixels, determining the position of each puck center to sub-pixel precision. The position of the magnet was marked on the surface of the non-magnetic plate and tracked by a similar process.

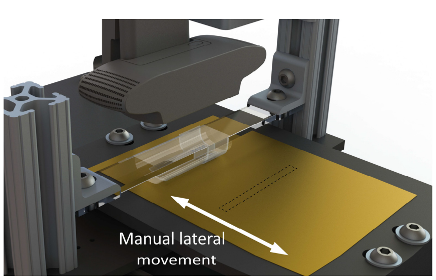

Figure 3. Set up used to record the pucks' movements as they slide across a static bar magnet (represented by the dash box) under a brass plate.

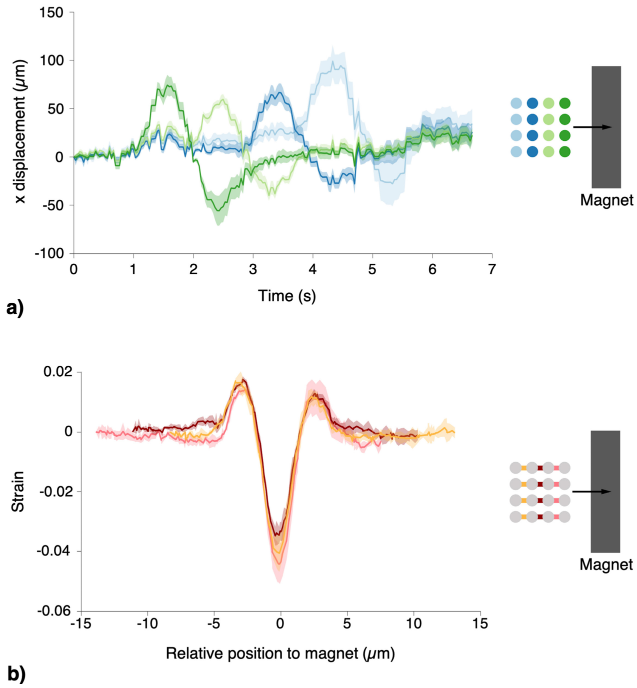

Figure 4. a) Average x-displacement of each puck column as they pass over the magnet, and b) Average strain between each puck column as a function of their distance from the magnet.

When the tactile device was passed over a bar magnet placed perpendicular to the axis of motion, the pucks exhibited a bilateral displacement (Δx) (fig. 4a) with respect to the puck array centroid along the x axis. This displacement had an average peak-to-peak amplitude across all pucks of 113 ± 32 μm, with an average peak positive displacement (Δx_p) of 54 ± 17 μm and an average peak negative displacement (Δx_n) of -48 ± 17 μm. As the device approached the magnet, the pucks would be displaced towards the magnet, in the direction of finger motion. As the device moved away from the magnet, the pucks would be displaced towards the magnet, against the direction of finger motion. Each column of pucks responded to the magnet independently, and the magnitude of this response was reliably correlated with the distance between the puck column and the center of the magnet (x_m).

As seen in figure 4b, the pucks began to displace as they approached within 5 mm of the magnet center and returned to an undisplaced state as they passed the magnet center by 5 mm. Δx_p and Δx_n were measured at x_m = 1.7 ± 0.4 mm and x_m = -0.8 ± 0.4 mm respectively. Given the magnet's width of 3 mm, this suggests that the pucks exhibited their strongest lateral response as they passed near the edges of the magnet. The asymmetry of these x_m values could have been a result of inaccuracies when marking the position of the magnet.

The pucks exhibited similar average peak displacements between finger motion along the positive (Δx_p = 54 ± 20 μm and Δx_n = -48 ± 14 μm) and negative (Δx_p = 54 ± 12 μm and Δx_n = -47 ± 20 μm) x directions. However, there was a small decrease in response between faster (8.2 mm/s) and slower (2.8 mm/s) finger motion (Δx_p = 49 ± 15 μm, Δx_n = -44 ± 17 μm, and Δx_p = 59 ± 18 μm, Δxn = -51 ± 17 μm respectively). These average peak displacements, on the order of ± 50 μm, met the threshold for tactile intelligibility [15].

Strain in the Ecoflex substrate between pucks was measured as the percent change in the distance between adjacent pucks in the same row with respect to an unstrained state (fig. 4b). Zero crossings in shear strain distributions are typically found at tactile edges [21]. These occurred when strain elements had x_m = -1.3 ± 0.3 mm and x_m = 2.1 ± 0.4 mm, which corresponded to the edges of the magnet.

IV. Psychophysical Experiments

With the understanding that the puck array could provide spatially distributed tactile cues, two psychophysical studies were conducted to assess its effectiveness. In the first study, performances across a real tangible surface (3D printed bumps), a 4 × 4 ferromagnetic array, and a single ferromagnetic patch (covering the same area as the array) was compared. For each case, participants were tasked with identifying the orientation of an angled magnet. The second experiment compared only the ferromagnetic array and a single ferromagnetic patch. The participants were directed to place their fingers at specific locations on a square magnet and variability in their selected positions was compared.

A. Participants

11 subjects (aged 26 ± 3 years, one left-handed, 4 females) participated in the experiments. Subject participation was approved by the Northwestern Institutional Review Board, and subjects were paid for their time.

B. Experiment 1

Figure 5 shows the experimental setup. Participants used their dominant index finger when interacting with the apparatus and could freely explore a circular area of 100mm^2. They could not see their dominant hand and wore headphones playing pink noise to cancel any sounds produced by the apparatus. They interacted with three stimuli: i) array, ii) patch and iii) tactile. In the array and patch cases, they wore the respective wrap on their index fingers and interacted with a 60 × 3 mm magnet under a 0.254 mm thick plate. With the tactile stimulus, their bare finger was used, and the surface consisted of raised bumps (1.8 mm diameter, 0.3 mm height) spaced with a center-to-center distance of 2.6 mm to create a 4.4 × 59 mm bar. A blue marker was placed on the top of their finger and a camera was mounted above to record exploratory movement.

The experiment consisted of 24 trials for each stimulus where the magnet or raised bumps were randomly moved to 1 of 6 orientations (0°, 30°, 60°, 90°, 120°, or 150°, where 0° is along the x-axis and angles are measured positive counterclockwise) (fig. 6a). After each trial, the participant selected the orientation they believed matched that of the bar. Before starting each stimulus, the participant was also given time to explore the different angled positions to familiarize themselves with the experimental platform.

Figure 5. Experimental setup for experiment 1 and 2.

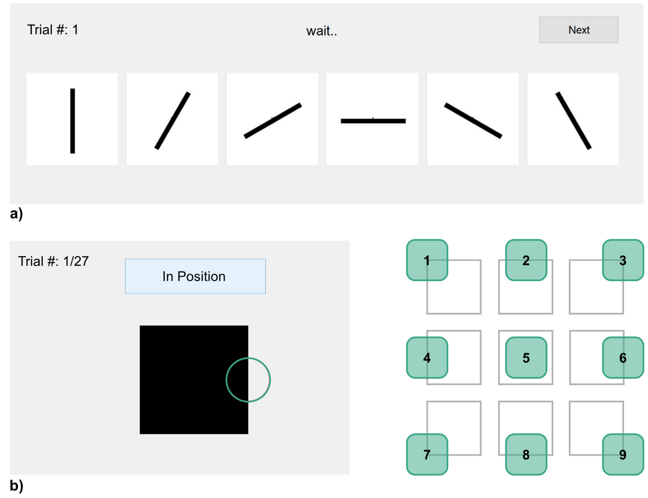

Figure 6. a) GUI interface of experiment 1, b) GUI interface of experiment 2 and 9 positions' location randomly displayed to the participants. The grey and green squares are the relative sizes between the fixed magnet the participants interact with and the active array/ patch on their index finger.

C. Experiment 2

The same apparatus of experiment 1 was used, but the participants interacted with a fixed 12.7 × 12.7 mm magnet instead. Participants were shown 1 of 9 positions relative to the magnet (fig. 6b) and tasked to place their index finger at the corresponding location. They could freely explore with no time constraints, and once they determined their finger was at the specified position, they held it still for 2 seconds and lifted it off before starting the next trial. This was repeated 27 times and performed with both the array and single patch. Similar to experiment 1, a marker was placed on top of their index finger to track its position.

V. Results

A. Experiment 1

For the tactile, patch, and array stimuli, accuracies were 96.97%, 83.33%, and 92.93% respectively. The exploration paths, however, were markedly different in the three cases (fig. 7). The paths were further analyzed by determining the instantaneous movement direction in the world frame at intervals of 1/60 seconds, and grouping these directions such that each group corresponded to the 6 orientations of the bar (e.g. angles ranging between 90 ± 15° were grouped together). Bidirectional movements were also considered in each group. The proportion of total distance traveled within each group is shown in figure 8 and is categorized by either the stimulus or bar's orientation. For visual clarity, the data were repeated from 150° to 345° at the opposite angles (e.g. 210° is equivalent to 30°, 330° to 150°).

It was observed that participants tended toward one of two exploration behaviors, either tracing along the bar directly ("match" strategy) or moving in a zigzag fashion along the 0° line regardless of the bar's orientation ("zero" strategy). To capture these quantitatively, a matrix of the 6 possible orientations of the bar × the 6 instantaneous movement directions (bidirectional) was created. For the zero strategy, a 1 was entered in the cell for zero-direction movement at all bar orientations, and for the match strategy, a 1 was entered for each cell where the movement and bar's orientations matched, with zeros elsewhere. For each participant, Pearson correlations were then performed between each weighted matrix (representing strategy) and the data (percentages of distance traveled in the given orientation), by type of stimulus. A r-value of 0.33 was needed to reach significance for any correlation. The mean correlations across participants by strategy and stimulus are shown in Table 1.

TABLE I. MEAN CORRELATION OF EACH STIMULUS TO EACH STRATAGY

Strategy	Stimulus		
	Tactile	***Patch***	***Array***
Zero	0.301	0.602	0.538
Match	0.810	0.423	0.234

A 2-way ANOVA on the factors of stimulus and strategy using the measure of the correlated exploration angles showed there was no effect of strategy, but there was a statistically significant interaction between stimulus and strategy ($F(2,16) = 9.682$, $p = 0.002$, $\eta^2_p = 0.548$). As such, a 1-way ANOVA for each strategy was performed and both show a significant effect of stimulus ($F(2,16) = 5.345$, $p = 0.017$, $\eta^2_p = 0.401$ and $F(2,16) = 10.248$, $p = 0.001$, $\eta^2_p = 0.562$ for zero and match strategy respectively).

Lastly, t-tests showed that the proportion of total distance participants spent moving in the same direction as the bar's orientation when using either the array or patch was significantly different from that of the tactile surface ($p = 0.02$ for tactile/ patch and 0.003 for tactile/ array). Similarly, there were significant differences between the array and tactile stimulus ($p = 0.03$), and patch and tactile stimulus ($p = 0.01$) when participants moved along the 0° axis.

B. *Experiment 2*

A point cloud of the participant's index finger position at the 9 locations for both stimuli is seen in figure 9a. The standard deviation ellipse (SDE) was also plotted for each position to compare the variations between the stimuli. Two categories of positions were also considered: height and left-to-right (L2R), and each category included three groups. Top (positions 1, 2, and 3), middle (positions 4, 5 and 6) and bottom (7, 8 and 9) for height, and left (positions 1, 4, and 7), middle (positions, 2, 5, and 8) and right (positions, 3, 6, and 9) for L2R. A 2-way ANOVA on the factors of stimulus, height, and L2R on the measure of noise (distance between a given point and the ellipse centroid) was performed. The sole significant effect was that of that stimulus factor, ($F(1,11) = 12.3$, $p = 0.005$, $\eta^2_p = 0.528$). The noise for each position was compared in figure 9b and showed that the noise for the patch was always higher than that of the array. No systematic bias was seen for any location or stimulus.

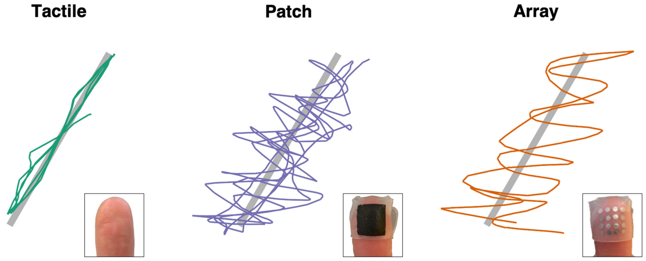

Figure 7. Exemplary exploration paths and the respective wraps on the subject's index finger (bare finger was used for the tactile stimulus) when using either the tactile, patch, or array stimulus.

VI. Discussion

A. *Experiment 1*

As seen in figure 8a, when given the tactile stimulus, the participants tended to move their fingers in the same direction as the bar's orientation, indicating that they could trace the bar well. This is further observed in its high correlation value to the match strategy ($r = 0.815$). This was expected as the raised bumps provided haptic information in both tangential and normal directions. Thus, treating this as the baseline, the array and patch stimuli are compared against it to determine their effectiveness.

For the patch stimulus, its mean correlation to the match strategy ($r = 0.423$) indicated that participants would trace the bar, but at a significantly lesser rate compared to that of the tactile stimulus ($r = 0.810$). When given the array stimulus, this tracing behavior decreased further ($r = 0.239$), but there was no significant difference between the patch and array.

Instead, when wearing the patch or array, participants tended to move along the 0° line regardless of the bar's orientation (as seen in figure 8b where the spokes remained largest along 0° and $r = 0.602$ and 0.538 to the zero strategy for the patch and array respectively). This also suggests that the larger spokes seen for the patch and array stimulus when the bar is in its 0° position are due to the exploration behavior chosen, and not the ability to trace the bar's position.

Thus, although the array and patch provided enough haptic information to discern different angled lines, it was not sufficient for a participant to trace the bar without strategic control. It should be noted that only with the patch did the correlation to both strategies reach significance, and there was no significant difference in the two behaviors. In comparison, the exploration pattern of the array stimulus was only significant with the zero strategy. This difference could be explained by the lack of edge information the patch provides. The patch is a continuous piece of flexible ferromagnetic material that provides global but not local shear information. Therefore, moving back and forth across the magnet does not provide high spatial frequency information that could be used to localize the edges, and it forces the wearer to attempt tracing the bar to estimate its orientation.

This same reasoning can be applied to the array where the participants would rather move their fingers across the bar instead of along it. As seen from the analysis of the puck's lateral movements, the pucks can provide localized shear within the contact patch. However, as they cannot provide normal displacements, the most intense sensation arise when moving across the bar. This could explain why participants chose to rely solely on the zero-exploration technique.

Despite the patch causing participants to exhibit behaviors more similar to the tactile stimulus, the accuracy of their orientation selection was the lowest at 83.33%. This could suggest that the participants were not obtaining the same haptic feedback when interacting with the patch and tactile stimulus. Lederman and Klatzky [5] noted that spatially distributed forces were required to accurately perceive 2D orientations. However, due to the lack of edge information the patch provides, the tracing behaviors observed might instead be an attempt to obtain kinesthetic feedback, which alone was not sufficient and could account for the lower accuracy. Instead, the array stimulus was able to provide this tactile feedback, and thus had a higher accuracy of 92.93%.

B. *Experiment 2*

As seen in figure 9a, the centroids' location of the SDEs for the array and patch stimulus showed that participants were able to generally perceive each distinct location. However, the variability in doing so was always higher when wearing the patch (fig 9b). This suggests that although there was no statistical difference in the accuracy, the array helped increase the precision in locating points along a square. This result supports the inference from experiment 1 that the patch does not provide enough information to precisely localize edges. It was expected that the difference was the smallest at the center of the square, as exact edge information was not necessary to find its location. Overall, the lower noise of the array indicates that it conveyed spatial geometric information better than the patch could.

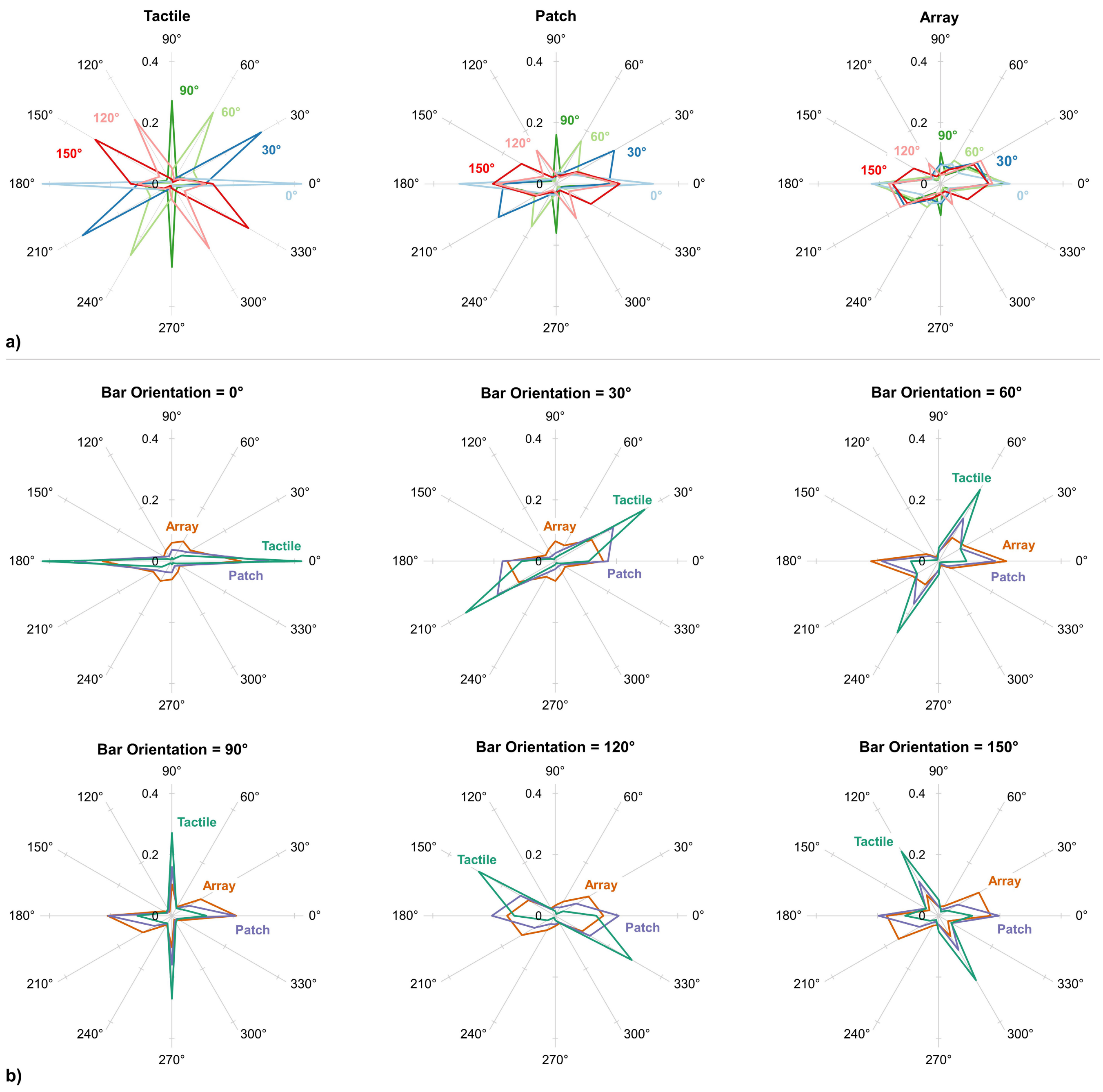

Figure 8. Percent of total distance travelled for each exploration group sorted by a) stimulus where each series corresponds to the bar's orientation, and b) bar's orientation where each series corresponded to a stimulus the participants interacted with.

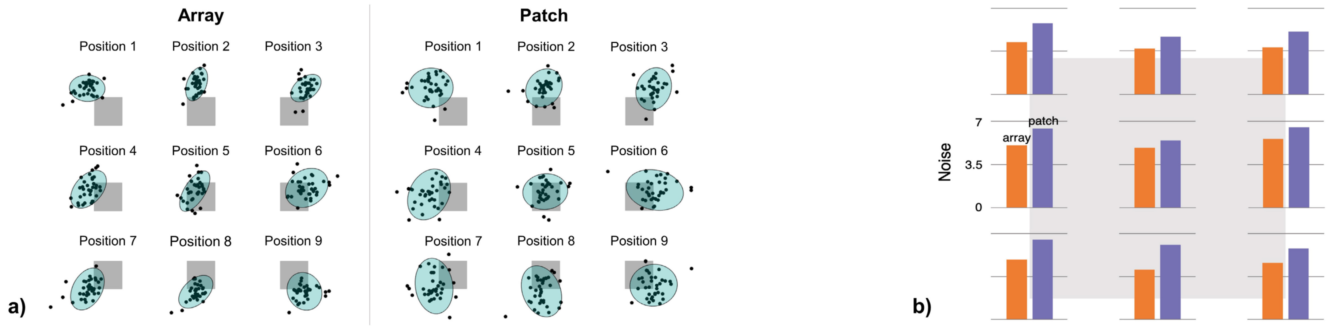

Figure 9. a) Point clouds of the participant's final chosen location for each position when interacting with the array or patch stimulus. b) Noise (average distance from point's location to the SDE centroid) comparisons of patch and array stimulus for each position.

VII. Conclusion

The experimental results demonstrated that the use of lateral forces in an array is a viable method to generate tactile information and this may be used to discern geometric features. However, exploration behaviors suggested that lateral displacements alone may not be sufficient to enable tracing behaviors similar to those seen with real tactile patterns.

The use of pucks interacting with a separate surface also allowed for the design of a thin and soft device, but the current design does not allow for individual control of the pucks, and its movements are dependent on the tightness of the magnet's magnetic field lines. As such, future work includes using electroadhesion as an actuation technique as fabricating thin, flexible, and low-profile electrode pucks is possible, and it allows for them to be individually controlled. However, in contrast to ferromagnetism where the attraction caused the pucks to move, electroadhesion creates a braking force that opposes the motion of the finger. Therefore, this opposite behavior will have to be further investigated as well.

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