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Affective Touch with Mid-Air Ultrasound: A Psychophysical Comparison with Real Materials

Rika Oya, Ryoya Onishi, Soichiro Matsumura, Zen Somei, Shun Suzuki, Hiroyuki Shinoda, *Member, IEEE*, and Ryo Kitada

Abstract—Affective touch has attracted significant interest due to its positive effects on child development and adult well-being. Studies showed that light and slow stroke of soft brush on hairy skin elicits affective sensation by activating C-Tactile fibers. Mid-air haptics, which uses focused ultrasound to create tactile sensations in free space, offers a promising method for eliciting affective changes. However, it remains poorly understood to what extent mid-air haptics can produce the perception similar to a brush stroke on hairy skin. Here, we conducted a psychophysical study comparing the tactile perception of mid-air ultrasound stimulation with that of real materials (sandpaper, aluminum resin, urethane rubber, cloth, and soft brush). Participants rated each stimulation on the dorsum of hand along three affective touch dimensions (pleasantness, surprise, ticklishness) and three discriminative touch dimensions (smoothness, softness, warmth). Univariate analyses revealed that ultrasound stimuli differed from aluminum resin, sandpaper, and urethane rubber in one or more dimensions of discriminative touch. Ultrasound stimulation with 10 Hz amplitude modulation significantly felt more pleasant than sandpaper, while no consistent differences between ultrasound and real textures ratings was observed in surprise and ticklishness. Multivariate analyses showed that ultrasound stimuli with amplitude modulation at 10 Hz and 100 Hz were significantly closer to real textures than unmodulated ultrasound. Questionnaires showed that over half of the participants identified ultrasound stimulation as a brush or cotton. These findings suggest that mid-air haptics can evoke perceptual attributes overlapping with those of real textures, including soft brushes, on hairy skin. Moreover, amplitude modulation may enhance the perceptual resemblance to realistic textures.

Index Terms—Affective touch, airborne ultrasound, discriminative touch, Mid-Air haptics.

I. INTRODUCTION

Interpersonal touch plays a vital role in cognitive and emotional development during childhood [1], [2], facilitates the formation of social bonds [3], [4], [5], and promotes psychological and physical well-being in adulthood [6], [7], [8]. Physical contact with a close friend or partner has also been shown to alleviate both physical and emotional distress [9], [10].

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the local ethics committee at University of Tokyo (approval number: 23-491) and Kobe University (approval number: 2023-5). The work was supported by a grant from the Moonshot Research and Development Program Japan to Hiroyuki Shinoda (grant number JPMJMS239E-01) and Ryo Kitada (JPMJMS239E-02), and MEXT/JSPS KAKENHI to Ryo Kitada (25H00581). *Rika Oya and Ryoya Onishi equally contributed to the work.

Consequently, there has been a growing body of research aimed at elucidating the nature and mechanisms of affective touch and exploring its potential applications.

A number of previous studies have demonstrated the role of a unique class of unmyelinated afferent fibers—known as C-tactile (CT) fibers—in mediating the perception of tactile pleasantness. These fibers are located in hairy skin and respond optimally to slow, gentle stroking [11], [12], [13]. Stroking at velocities between 10 and 100 mm/s has been shown to elicit the most pleasant sensations [11], [12], [13], [14], [15], and this perceived pleasantness closely correlates with the firing rate of CT fibers, rather than with the activity of other mechanoreceptors, which detect mechanical deformation of the skin [12], [13]. Notably, stroking the forearm or dorsum of the hand with a soft brush can induce a pleasant experience even in a patient lacking large myelinated afferents [16]. Given that slow, light skin stimulation commonly occurs during interpersonal interactions, it has been proposed that CT fibers are particularly tuned to elicit pleasurable sensations during social touch—a concept known as the “social touch” hypothesis [17], [18]. As the activation of CT afferents during social touch can be associated with reinforcing, anxiety-reducing, and potentially pain-relieving effects [19], there is significant value in developing systems that can flexibly stimulate hairy skin regions innervated by CT fibers.

One promising approach to achieving this goal is the use of an airborne ultrasound tactile display, also known as a mid-air tactile display [20], [21], [22]. This technology generates focal points of airborne ultrasound using a phased array system [23], which can induce vibrotactile, pressure, and thermal sensations on the skin [20], [24], [25], [26]. Mid-air tactile displays offer high spatiotemporal controllability and deliver tactile sensations without physical contact, making them suitable for reproducing the tactile properties of real objects and enabling various potential applications [27], [28], [29].

One line of the previous studies has explored the extent to which mid-air tactile displays can present realistic textures on the participant’s palm [30], [31]. In our earlier work, we

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demonstrated that participants could identify a "soft brush" sensation among three mid-air-generated textures (soft brush, sponge, and towel) with an accuracy ranging from 55% to 78% [30]. In another study, nine types of virtual textures were created and evaluated in terms of roughness, pleasantness, and activity [31]. Their findings indicated that some textures, such as calico and muslin, were perceived more similarly to real materials than others, like buckram. They also found that the system could produce differences in perceived roughness between certain textures. However, there were no significant differences observed in participants' ratings of pleasantness and activity levels across textures. Thus, while mid-air ultrasound can create tactile stimulation similar to a soft brush on glabrous skin, it remains unknown whether this finding extends to hairy skin, which differs from glabrous skin both in C-tactile fiber density [32] and in the presence of mechanoreceptors specific to hairy skin, such as hair and field units [12].

Another line of research has examined affective responses to ultrasound stimulation applied to hairy skin [33], [34]. These studies demonstrated that the movement speed of mid-air ultrasound influences perceived pleasantness. However, the observed effects of speed were not consistent with those reported for real textiles; greater pleasantness was elicited at lower or higher speeds than the optimal range associated with CT fiber activation. Thus, it remains an open question whether mid-air ultrasound can elicit sensations comparable to a gentle stroke with a soft brush—stimuli commonly used in studies investigating tactile pleasantness mediated by CT fibers.

The main goal of the present study was to examine the extent to which mid-air ultrasound stimulation can evoke perceptual attributes similar to real textures on hairy skin, with attention to soft brush commonly used in affective touch research. To this end, we conducted a psychophysical experiment comparing tactile perceptions elicited by mid-air ultrasound stimulation with those evoked by real textures, including sandpaper, aluminum resin, urethane rubber, cloth, and a soft brush. Both real textures and ultrasound stimulation were applied to the dorsal side of the hand using comparable speeds and normal force. For the ultrasound condition, we systematically manipulated the tangential movement speed across the skin, ranging from 3 mm/s to 100 mm/s. Participants rated each stimulation along three discriminative touch dimensions (smoothness, softness, warmth) [35], [36] and three affective touch dimensions (pleasantness, surprise, ticklishness). We used the three affective dimensions because affect is represented in valence and arousal [37] [38], whereas ticklishness of light touch [39] can cause both pleasantness and unpleasantness. We compared real textures and mid-air ultrasound stimulation in each dimension (univariate analysis) and then compared them beyond each dimension using a multivariate approach [40].

We hypothesized that similar patterns of speed dependent perception are observed between ultrasound stimulation and real textures, and that ultrasound stimulation could be perceived more like soft brush than aluminum resin and sandpaper. Cloth and urethane rubber were included for exploratory purposes. Finally, previous studies developed a system to add vibration-like sensations by modulating amplitudes of ultrasound stimulation [30]. Thus, we tested if amplitude modulations can

make ultrasound stimulation perceived as closer to realistic textures.

II. METHODS

A. Participants

Twenty-nine naïve adults (14 men and 15 women) participated in the study via a temp agency (Agekke Corp., Tokyo). Their mean age was 31.0 years (range: 22–40 years). All participants were right-handed, as assessed by the Fazio Handedness Inventory [41], and none had any injuries on the skin areas where tactile stimuli were applied. All participants self-reported no prior history of tactile dysfunction, though we did not assess tactile sensitivity using classical procedures. The study protocol was approved by the local ethics committees at the University of Tokyo (approval number: 23-491) and Kobe University (approval number: 2023-5). Written informed consent was obtained from all participants prior to participation. All procedures were conducted in accordance with the approved ethical guidelines. The sample size was determined based on previous studies that demonstrated the effect of movement speed of real textures on pleasantness [14], [15].

B. Experiment setup

We developed an apparatus to stimulate the same skin region using either a mid-air ultrasound tactile display or real textures (Fig. 1). The setup consisted of an airborne ultrasonic phased array, a robotic arm (DOBOT Magician, Dobot Robotics, Shenzhen, China), a depth-sensing camera, a black cloth, and a cushioned armrest. The depth-sensing camera with RGB detection capabilities (RealSense™, Intel, Santa Clara, CA, US) was used to measure the distance between the device and the participant's hand [42]. For real texture stimulation, each material was attached to the end of the robotic arm. Airborne ultrasonic stimulation was delivered using a phased array system (AUTD3; [23]) composed of eight phased array units connected via Ethernet cables. The system was controlled using the pyautd3 library.

Participants were seated in a chair and viewed a computer display, with their left hand resting on a numeric keypad used to initiate and evaluate tactile stimulation. Their right forearm and hand were placed inside the apparatus, which was positioned to the right of the participant (Fig. 1(a)). The apparatus was not visible to participants, as it was both laterally positioned and concealed by a black cloth covering the front. To mask operational sounds from the ultrasonic phased array and robotic arm, participants wore headphones (HD300Pro, Sennheiser, Wedemark, Germany) and listened to continuous pink noise throughout the experimental sessions.

C. Tactile stimulation

Tactile stimuli were applied to the dorsum of the right hand and consisted of three mid-air ultrasound stimuli (US) and five real materials. The ultrasound stimuli included a non-modulated focal point (US0Hz) and amplitude-modulated focal points at 10 Hz (US10Hz) and 100 Hz (US100Hz). The amplitude modulation was intended to capture aspects of tactile

stimulation produced by real textures that typically produce vibration below 400 Hz on skin [43].

We used real materials that varied across three perceptual dimensions of discriminative touch [36]: roughness, softness, and warmth. The selected materials included aluminum resin, a soft brush, cotton cloth, sandpaper (#240 grit), and urethane rubber (Fig. 1(c)). Except for the brush, all materials had a standardized shape—a spherical segment with a 5-cm diameter base and 1.3-cm height. The soft brush (J601, HAKUHODO, Kumano, Japan) was made of goat hair and used for cosmetic applications.

Aluminum resin and sandpaper were included as negative controls due to their textural dissimilarity from the soft brush. In contrast, cotton cloth and urethane rubber were selected for their relatively high pleasantness, as reported in previous studies [15], [44]. The urethane rubber (Bioskin #18, Beaulax Co. Ltd., Saitama, Japan) was covered with a plastic membrane and had a compliance of 6.0 mm/N when pressed with a 1 cm² probe [45]. For consistency in surface properties, the cotton cloth and sandpaper were affixed to a harder urethane rubber substrate (1.9 mm/N).

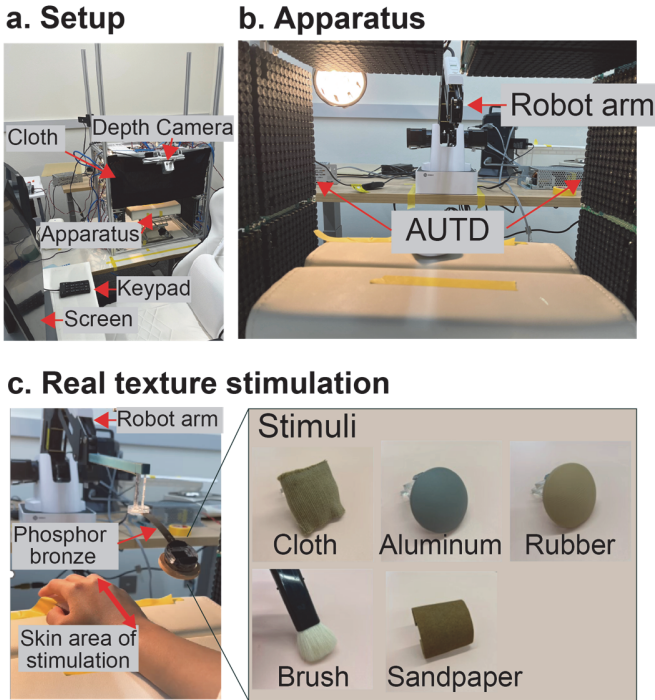


Fig. 1. Experimental setup and stimuli. (a) Setup. The participant was seated in front of a screen with their right arm placed in the apparatus. They used a keypad with their left hand to provide responses. For visualization purposes, the keypad is shown on the right side of the table. (b) Apparatus. The same target skin area was stimulated using either an Airborne Ultrasound Tactile Display (AUTD) or a piece of real texture attached to a robotic arm. (c) Real texture stimulation. One of the textures was mounted on the robotic arm and applied to the target skin region. The contact force was controlled based on distance measurements from a depth-sensing camera.

We roughly matched the contact area of the stimulation (approximately 1 cm²) and the normal force applied to the skin (approximately 0.03 N). Force level corresponded to the maximum level that mid-air ultrasound stimulates the skin uniformly across the entire hand using the eight ultrasound phased arrays. The position of the real texture stimuli was controlled using the depth-sensing camera, while the force was fine-tuned with a phosphor bronze plate placed between the real textures and the robotic arm (Fig. 1(a) and 1(c)). Each stimulus was stroked twice over a 5 cm distance from distal to proximal on the right hand. Stroke speeds were tested at four levels: 3, 10, 30, and 100 mm/s. The slowest speed (3 mm/s) was expected to be less pleasant [12], [13], [14], [15] and to elicit less CT fiber activity than the higher speeds [12], [13].

D. Experiment design and procedure

The main experiment included four sessions: two real-texture sessions and two ultrasound sessions. Each real-texture session comprised 20 trials (5 types of textures $\times$ 4 stroke speeds), while each ultrasound session comprised 12 trials (3 types of ultrasound stimuli $\times$ 4 stroke speeds). The order of sessions and the presentation of tactile stimuli within each session were pseudo-randomized. A short break was provided between the sessions.

To compare ultrasound stimulation with tactile stimulation from real textures, participants rated each stimulus along six perceptual dimensions using an 11-point scale (0–10). Three of these dimensions pertained to affective touch: pleasantness (0 = very unpleasant; 10 = very pleasant), surprise (0 = not surprising at all; 10 = extremely surprising), and ticklishness (0 = not ticklish; 10 = extremely ticklish). Pleasantness and surprise were assumed to correspond to the valence and arousal axes of Russell's circumplex model of emotion [37], [38]. Surprise is considered the basic emotion with the highest arousal while being valence-neutral among the basic emotions [46].

Ticklishness was included as an additional dimension, as it may involve both pleasant and unpleasant sensations [39], which are not fully captured by the circumplex model. The remaining three dimensions reflected discriminative touch: softness (0 = very hard; 10 = very soft), smoothness (0 = very rough; 10 = very smooth), and warmth (0 = very cold; 10 = very warm). These dimensions were selected based on prior studies on tactile perception [35], [36]. After each stimulation, participants pressed a button with their left hand to rate how each of the following dimensions was perceived when being touched, in the following order: pleasantness (kokochiyosa in Japanese), surprise (odoroki), ticklishness (kusuguttasa), smoothness (namerakasa), softness (yawarakasa), and warmth (ataதாகasa). To ensure that the term surprise would be interpreted not as a discrete emotion category but rather as the arousal dimension with neutral valence, we also provided the synonymous expressions tense (kinchosuru) and alert (megasameru) for reference.

In each trial, tactile stimulation began after participants initiated the trial via a key press. A fixation point was displayed on the screen during stimulation to control for visual perception.

Following the stimulation, participants entered their ratings using a numeric keypad with their left hand and confirmed their responses on the screen. Participants were instructed to evaluate each stimulus in a way that ensured consistency across all blocks.

After the main experiment, the participants went through the supplementary experiment session. Because the normal force in the main experiment was lower than typical experiments used to stimulate CT fibers and cause pleasantness [12], [13], we examined the effect of normal force on pleasantness in the brush stimulation. This session comprised 16 trials (2 force levels $\times$ 4 speeds $\times$ 2 repetitions). After these sessions, participants completed questionnaires.

E. Analysis

We used MATLAB (R2022b, MathWorks, Natick, MA, USA), R package (<https://cran.r-project.org/>) and JASP (<https://jasp-stats.org/>) for data analysis. Both classical univariate and multivariate analyses were conducted. For the univariate analyses, we performed three-way mixed ANOVAs on each rating, with one between-subjects factor (sex) and two within-subject factors: texture (three ultrasound types and five real textures) and speed (four levels). We included sex as a between-subject factor, given prior evidence that female participants tend to exhibit more positive responses to affective touch compared to males [47]. Greenhouse-Geisser corrections were applied to all degrees of freedom. ANOVA is robust to non-normality under the central limit theorem, with controlled Type-I error rates [48], [49]. Post-hoc pairwise comparisons were conducted using paired t-tests. Family-wise errors were controlled with Bonferroni correction, and corrected p values were reported as P_{FWE} . Given our prior hypothesis that ultrasound stimuli would differ from aluminum resin and sandpaper, we used one-tailed paired t-tests to test compare ultrasound stimuli with aluminum resin and sandpaper.

To examine (1) whether amplitude modulation enhances the perception of ultrasound stimuli as more similar to real textures, and (2) which real textures are perceptually most similar to ultrasound stimuli, we conducted multivariate analyses. Unlike univariate analyses, these multivariate approaches considered all perceptual ratings simultaneously to evaluate the perceptual distances between each pair of stimulus conditions. This method is similar to representational similarity analysis [40], [50], [51]. We first visualized the perceptual relationships among stimuli using classical multidimensional scaling (MDS) based on the group mean ratings. To perform statistical analysis at the individual level, we employed a summary statistics approach: for each participant, we calculated the perceptual distance from each ultrasound stimulus to each real texture by averaging across the four stroke speeds. Thus, for each ultrasound condition, we obtained five distances—one for each real texture. We used Mahalanobis distance to quantify perceptual differences between stimuli, as there would be correlations among perceptual dimensions [44], [52]. Finally, to examine agreement of ratings across blocks, the intraclass correlation coefficient [ICC(3, 1), absolute agreement] was calculated using the *irr* package in R.

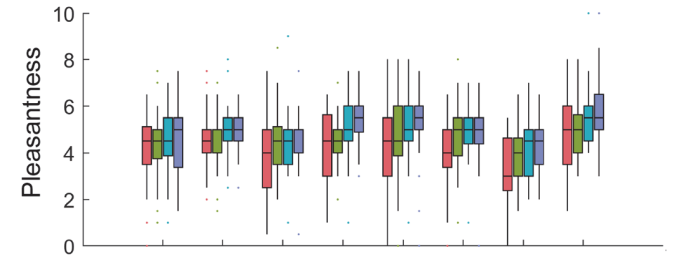
III. RESULTS

We first conducted univariate analyses on the six perceptual dimensions, followed by multivariate analyses to examine the overall perceptual structure.

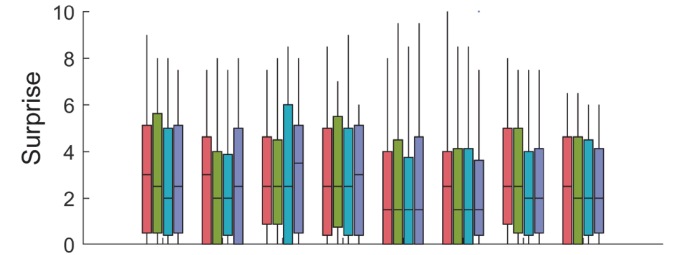
A. Univariate analyses

1) Pleasantness: We initially examined the effect of speed on pleasantness ratings (Fig. 2(a)). A three-way mixed ANOVA (8 levels of texture types $\times$ 4 speed levels $\times$ 2 sexes) revealed significant main effects of texture [$F(4.4, 118.7) = 5.77$, $p < 0.001$, $\eta_p^2 = 0.18$] and speed [$F(1.5, 39.5) = 16.91$, $p < 0.001$, $\eta_p^2 = 0.39$]. However, no significant main effect of sex or interaction effects, including the three-way interaction, were observed (p values > 0.06).

a. Pleasantness



b. Surprise



c. Ticklishness

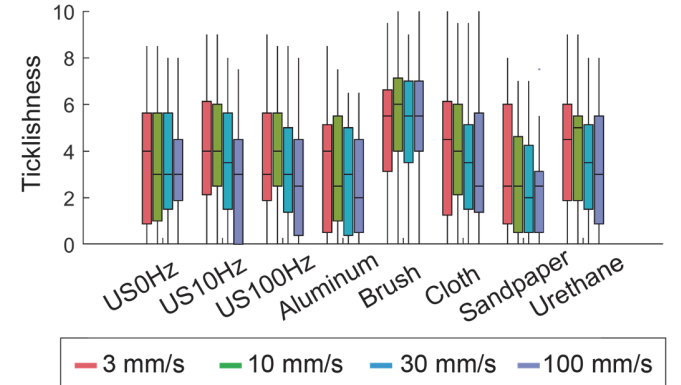


Fig. 2. Ratings for perceptual dimensions of affective touch. Boxplots show ratings for (a) pleasantness, (b) surprise, and (c) ticklishness of 29 participants. US0Hz, US10Hz, and US100Hz represent ultrasound stimuli with no amplitude modulation (0 Hz), 10 Hz modulation, and 100 Hz modulation, respectively. Horizontal bars inside each box indicate median values, while the upper and lower edges of each box represent the 75th and 25th percentiles, respectively. See Figs. S1-S3 in the

supplementary information for the plots of main effects of texture type, speed level, and sex.

We then conducted post-hoc pairwise comparisons (paired t-tests with Bonferroni correction) on the speed factor averaged across textures (Table S1 in the supplementary material). The results confirmed that pleasantness ratings for 3 mm/s were significantly lower than those at all other speeds (P_{FWE} values < 0.01), and ratings at 10 mm/s were significantly lower than those at 30 and 100 mm/s (P_{FWE} values < 0.05). These results confirm our hypothesis that pleasantness ratings are higher at 10, 30, and 100 mm/s compared to 3 mm/s, both for ultrasound stimuli and real textures.

We then conducted post-hoc pairwise comparisons between textures (Table S2). To test our a priori hypothesis, we compared ultrasound stimuli with control textures (sandpaper and aluminum resin) using one-tailed paired t-tests with Bonferroni correction. The results showed that US10Hz was rated as significantly more pleasant than sandpaper [$t(27) = 3.20$, $P_{FWE} = 0.049$, $d = 0.59$], whereas no significant differences from sandpaper were observed for US0Hz and US100Hz (P_{FWE} values > 0.5). Pairwise comparisons among the real textures revealed that sandpaper was rated significantly less pleasant than urethane rubber, brush, and aluminum resin (P_{FWE} values < 0.05 , two-tailed). No other significant differences were observed.

2) Surprise: We then repeated the same analysis on each of the other affective dimensions. Fig. 2(b) shows patterns of surprise ratings. A three-way mixed ANOVA (8 textures $\times$ 4 speeds $\times$ 2 sexes) revealed significant main effects of speed [$F(2.0, 53.6) = 3.81$, $p = 0.029$, $\eta_p^2 = 0.12$] and of texture [$F(4.0, 111.1) = 2.51$, $p = 0.049$, $\eta_p^2 = 0.085$]. However, no significant interactions, including the three-way interaction, were observed (p values > 0.09). We then conducted post-hoc pairwise comparisons (with Bonferroni correction) on speed after collapsing the factors of texture. No significant differences were found (Table S3), although 3 mm/s was rated as marginally more surprising than 30 mm/s ($P_{FWE} = 0.052$). We also conducted the same t-tests on ratings of textures averaged over the speeds (Table S4). However, no significant effect was observed (P_{FWE} values > 0.13).

Collectively, no significant difference was observed between ultrasound stimuli and real textures.

3) Ticklishness: Fig. 2(c) shows patterns of ticklishness ratings. The same three-way mixed ANOVA revealed significant main effects of texture [$F(3.6, 97.8) = 10.72$, $p < 0.001$, $\eta_p^2 = 0.28$] and of speed [$F(1.9, 52.1) = 14.79$, $p < 0.001$, $\eta_p^2 = 0.35$]. However, this ANOVA also revealed significant interactions between sex and texture [$F(3.6, 97.8) = 3.91$, $p = 0.007$, $\eta_p^2 = 0.13$], between texture and speed [$F(8.7, 234.8) = 3.04$, $p = 0.002$, $\eta_p^2 = 0.10$], and a three-way interaction among sex, texture, and speed [$F(8.7, 234.8) = 2.03$, $p = 0.039$, $\eta_p^2 = 0.07$].

Given the presence of the three way interaction, we conducted the following two types of post-hoc analyses. First,

we examined if speed-dependent patterns are consistent between sex. Simple effect analyses with one-way repeated-measures ANOVA (4 speeds) showed significant effects for US10Hz [$F(2.0, 25.5) = 7.83$, $p = 0.002$, $\eta_p^2 = 0.38$ for men; $F(2.0, 27.5) = 4.66$, $p = 0.019$, $\eta_p^2 = 0.25$ for women] and US100Hz [$F(2.2, 28.4) = 6.34$, $p = 0.004$, $\eta_p^2 = 0.33$ for men; $F(1.9, 25.9) = 5.45$, $p = 0.012$, $\eta_p^2 = 0.28$ for women]. Post-hoc pairwise comparisons (with Bonferroni correction) showed that the score for US10Hz was significantly greater at 10 mm/s than 100 mm/s for both male and female participants ($P_{FWE} < 0.05$, Table S5 and S6).

Secondly, we conducted simple effect analyses using one-way repeated-measures ANOVA (8 textures) on ticklishness ratings at each speed of each sex (Table S7). These analyses on male participants showed significant main effects at all speed levels except for 3 mm/s [$F(3.8, 50.0) = 4.89$, $p = 0.002$, $\eta_p^2 = 0.27$ for 10 mm/s; $F(3.1, 40.6) = 4.11$, $p = 0.011$, $\eta_p^2 = 0.24$ for 30 mm/s; $F(2.5, 32.8) = 5.63$, $p = 0.005$, $\eta_p^2 = 0.30$ for 100 mm/s]. Post-hoc pairwise comparisons (with Bonferroni correction) showed that the ticklishness score for US10Hz was greater than that for sandpaper at 10 and 30 mm/s (P_{FWE} values < 0.05). Moreover, the rating for US100Hz was less than brush at 100 mm/s ($p = 0.008$). However, US0Hz showed no significant difference from real textures. No significant differences were found among the three ultrasound conditions (P_{FWE} values < 0.05). Among the real textures, ratings for the soft brush were significantly higher than those for the sandpapers at all speeds, higher than those for aluminum resin at 30 and 100 mm/s, and higher than that for urethane rubber at 30 mm/s (P_{FWE} values < 0.05).

The same one-way ANOVA for female participants showed significant main effects of texture at all speeds [$F(4.3, 59.9) = 8.23$, $p < 0.001$, $\eta_p^2 = 0.37$ for 3 mm/s; $F(2.6, 36.6) = 9.72$, $p < 0.001$, $\eta_p^2 = 0.41$ for 10 mm/s; $F(2.9, 40.2) = 6.32$, $p = 0.001$, $\eta_p^2 = 0.31$ for 30 mm/s; $F(3.3, 46.6) = 9.35$, $p < 0.001$, $\eta_p^2 = 0.40$ for 100 mm/s]. Post-hoc pairwise comparisons (with Bonferroni correction) revealed that ratings for US0Hz were significantly lower than brush, cloth, and urethane at 3 mm/s; lower than brush and cloth at 10 mm/s (P_{FWE} values < 0.05 , Table S8). The score for US10Hz was lower than brush at 3 and 100 mm/s and lower than cloth at 10 mm/s (P_{FWE} values < 0.05). The score for US100Hz was lower than brush at 3, 30 and 100 mm/s (P_{FWE} values < 0.05). No significant differences were found among the three ultrasound conditions (P_{FWE} values < 0.05). Among the real textures, ratings for sandpaper were lower than those for the brush at 10 and 100 mm/s (P_{FWE} values < 0.05), and lower than those for the cloth at 10 mm/s ($P_{FWE} = 0.041$). The soft brush condition also yielded higher ratings than the aluminum resin condition at 100 mm/s ($P_{FWE} = 0.036$).

Overall, comparisons of ticklishness ratings across textures revealed a few consistent patterns between male and female participants. Specifically, regardless of sex, soft brush strokes were rated as significantly more ticklish than the 100 Hz ultrasound stimulus and aluminum resin at 100 mm/s. Additionally, the brush was rated as significantly more ticklish than sandpaper at both 10 mm/s in both male and female

participants.

To summarize the affective dimension analyses, we observed comparable speed-dependent patterns of pleasantness across texture types. Moreover, the 10 Hz ultrasound stimulus was rated as more pleasant than sandpaper at all speeds. By contrast, no such speed-independent difference between ultrasound and real textures was observed for surprise and ticklishness. In the next section, we analyze the ratings related to the discriminative aspects of texture perception.

4) *Smoothness*: Fig. 3(a) shows the ratings of perceived smoothness. A three-way mixed ANOVA (8 textures $\times$ 4 speeds $\times$ 2 sexes) revealed a significant main effect of texture [$F(4.1, 110.8) = 21.88, p < 0.001, \eta_p^2 = 0.45$], as well as a significant interaction between texture and speed [$F(10.9, 293.5) = 3.72, p < 0.001, \eta_p^2 = 0.12$]. No significant three-way interaction was observed ($p = 0.85$).

Given the significant texture $\times$ speed interaction, we conducted two post-hoc analyses. First, we performed simple effect analyses using a one-way repeated-measures ANOVA (4 levels of speed) for each texture type (Table S9). This analysis revealed no significant main effects of speed for any of the ultrasound stimuli. In contrast, significant main effects of speed were observed for aluminum resin [$F(2.1, 57.7) = 18.75, p < 0.001, \eta_p^2 = 0.40$] and for soft brush [$F(2.3, 63.7) = 4.92, p = 0.008, \eta_p^2 = 0.15$]. Post-hoc pairwise comparisons showed that smoothness ratings for aluminum resin significantly differed across all speed combinations (P_{FWE} values < 0.05). For soft brush, ratings at 10 mm/s and 30 mm/s were significantly higher than those at 3 mm/s (P_{FWE} values < 0.05).

As a second analysis, we conducted simple effect analyses using one-way repeated-measures ANOVA (8 textures) separately at each speed (Table S10). Significant main effects of texture were observed at all speeds: 3 mm/s [$F(4.8, 135.2) = 16.30, p < 0.001, \eta_p^2 = 0.37$], 10 mm/s [$F(4.7, 131.3) = 18.36, p < 0.001, \eta_p^2 = 0.40$], 30 mm/s [$F(3.9, 109.9) = 14.75, p < 0.001, \eta_p^2 = 0.35$], and 100 mm/s [$F(4.2, 116.7) = 17.83, p < 0.001, \eta_p^2 = 0.39$]. Post-hoc pairwise comparisons revealed that the smoothness rating for sandpaper was significantly lower than all ultrasound and other real textures, regardless of the speeds (P_{FWE} values < 0.01). The score for US10 Hz was significantly greater than cloth at 3 mm/s ($P_{FWE} = 0.006$). Among the real textures, urethane rubber was rated smoother than cloth at all speeds (P_{FWE} values < 0.01) and smoother than aluminum resin at 3 mm/s ($P_{FWE} < 0.001$). Additionally, aluminum resin was rated smoother than cloth at 30 and 100 mm/s (P_{FWE} values < 0.05), and cloth was rated significantly less smooth than brush at 30 mm/s ($P_{FWE} = 0.017$).

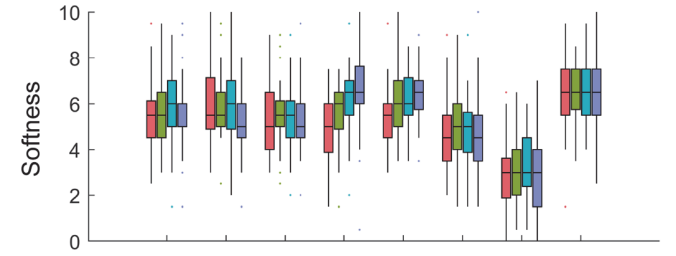
Collectively, ultrasound stimuli were significantly felt smoother than sandpaper, whereas US10Hz was rated felt smoother than cloth at a specific speed condition.

5) *Softness*: Fig. 3(b) shows the patterns of softness ratings. A three-way mixed ANOVA (8 textures $\times$ 4 speeds $\times$ 2 sexes) revealed a significant main effect of texture [$F(4.2, 114.4) = 23.28, p < 0.001, \eta_p^2 = 0.46$]. No significant main effects of

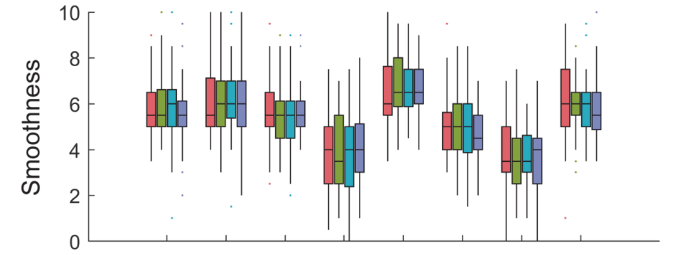
speed or sex, and no interaction effects, including the three-way interaction, were observed (p values > 0.1). Post-hoc pairwise comparisons (with Bonferroni correction) on textures revealed that all ultrasound conditions were rated significantly softer than aluminum and sandpaper (P_{FWE} values < 0.01). Additionally, US10Hz was rated softer than cloth, whereas US100Hz was rated harder than brush (P_{FWE} values < 0.01). No significant differences were found among the three ultrasound conditions.

Among real textures, brush and urethane rubber were rated significantly softer than aluminum and sandpaper (P_{FWE} values < 0.01). Brush was also rated significantly softer than cloth ($P_{FWE} < 0.001$), and cloth was rated softer than sandpaper ($P_{FWE} = 0.002$). Collectively, these analyses showed that softness ratings for the mid-air ultrasound stimuli were significantly different from those for aluminum and sandpaper. See Tables S11 and S12 for p values of pairwise comparisons.

a. Smoothness



b. Softness



c. Warmness

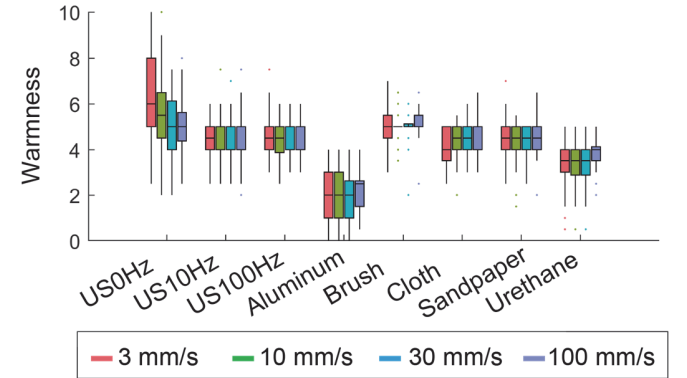


Fig. 3. Ratings of discriminative dimensions. Boxplots of ratings for (a) softness, (b) smoothness, and (c) warmness are shown ($N = 29$).

6) *Warmness*: Fig. 3(c) shows the patterns of warmness ratings. A three-way mixed ANOVA (8 textures $\times$ 4 speeds $\times$

2 sexes) revealed significant main effects of texture [$F(2.8, 75.0) = 52.68, p < 0.001, \eta_p^2 = 0.66$] and speed [$F(2.6, 69.4) = 3.54, p = 0.024, \eta_p^2 = 0.12$], as well as a significant interaction between texture and speed [$F(6.9, 186.0) = 7.23, p < 0.001, \eta_p^2 = 0.21$]. No significant three-way interaction was observed ($p = 0.66$).

Given the presence of texture $\times$ speed interaction, we conducted simple effect analyses using one-way repeated-measures ANOVA (4 speeds) for each texture. These analyses revealed significant main effects for US0Hz [$F(2.2, 60.6) = 15.29, p < 0.001, \eta_p^2 = 0.35$], aluminum resin [$F(2.5, 69.5) = 3.27, p = 0.034, \eta_p^2 = 0.11$], cloth [$F(2.4, 67.8) = 6.05, p = 0.002, \eta_p^2 = 0.18$], and urethane rubber [$F(2.5, 71.3) = 5.25, p = 0.004, \eta_p^2 = 0.16$]. Post-hoc pairwise comparisons showed that for US0Hz, warmth ratings at 3 mm/s were significantly higher than at all other speeds (P_{FWE} values < 0.01). No significant difference was observed for aluminum (P_{FWE} values > 0.12). Cloth was rated significantly warmer at 100 mm/s than at 3 and 10 mm/s, and urethane rubber was rated warmer at 100 mm/s than at all other speeds (P_{FWE} values < 0.05). No other significant differences were observed (Table S13).

We then performed simple effect analyses of warmth ratings for textures at each speed. One-way repeated measures ANOVA (8 textures) revealed significant main effects at all speeds [$F(2.6, 73.5) = 42.14, p < 0.001, \eta_p^2 = 0.60$ for 3 mm/s; $F(3.0, 83.1) = 37.46, p < 0.001, \eta_p^2 = 0.57$ for 10 mm/s; $F(3.7, 102.8) = 42.14, p < 0.001, \eta_p^2 = 0.60$ for 30 mm/s; $F(3.8, 105.9) = 42.98, p < 0.001, \eta_p^2 = 0.61$ for 100 mm/s]. Post-hoc pairwise comparisons (with Bonferroni correction) revealed that the rating for aluminum resin was significantly lower than that for all ultrasound stimuli and other real textures, regardless of speeds (P_{FWE} values < 0.001 , Table S14). Urethane rubber was rated significantly lower than US0Hz, US100Hz, soft brush, cloth, and sandpaper across all speeds (P_{FWE} values < 0.01). It was also rated lower than US10Hz at all speeds except 100 mm/s (P_{FWE} values < 0.01). US0Hz was rated significantly warmer than cloth at 3 mm/s and 10 mm/s (P_{FWE} values < 0.05), and warmer than US10Hz, US100Hz, and sandpaper at 3 mm/s (P_{FWE} values < 0.001). Additionally, the soft brush was rated significantly warmer than both cloth and sandpaper at 3 mm/s and 10 mm/s (P_{FWE} values < 0.05).

Collectively, mid-air ultrasound conditions were rated differently from aluminum resin, sandpaper and urethane rubbers across one or more discriminative touch dimensions, largely consistently across speeds. Next, we examined the relationships between ultrasound and real texture conditions using multivariate analyses.

B. Multivariate analyses

Fig. 4 shows the result of the classical multidimensional scaling (MDS) on the group mean data. The scree plot in Fig. 4(a) shows a reasonably clear elbow at the 3D solution. Fig. 4(b) shows each stimulation condition in 3D MDS solutions. Largely, speed conditions of the same texture appear to be clustered together. Ultrasound stimulation conditions (shown in

black and gray) were located close together, whereas US0Hz conditions were located differently from US10Hz and US100Hz conditions.

To statistically evaluate perceptual dissimilarity of clusters of three ultrasound conditions from clusters of the five real textures, we compared distances among these conditions. We used Mahalanobis distance that assumes correlation of 8 types of ratings (e.g., correlations between smoothness and softness). We initially measured distances for each participant and then collapsed the factor of speed in each participant. Fig. 5 shows the result of distances from each ultrasound stimulation. A three-way mixed ANOVA (3 types of ultrasound $\times$ 5 real textures $\times$ 2 sexes) on distance scores showed significant main effects of ultrasound types [$F(1.9, 52.1) = 11.16, p < 0.001, \eta_p^2 = 0.29$] and of real textures [$F(3.7, 99.9) = 13.06, p < 0.001, \eta_p^2 = 0.24$]. No significant interaction was observed (p values > 0.1).

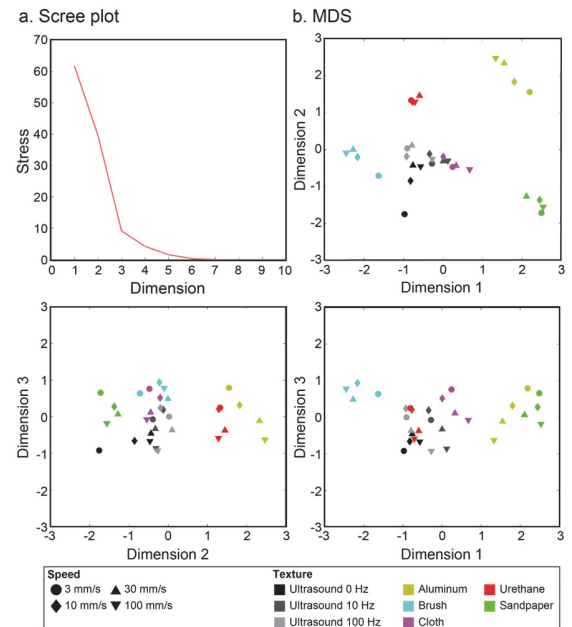


Fig. 4. Multidimensional Scaling (MDS) solutions for the group results. (a) Stress values of MDS solutions plotted as a function of dimensionality. (b) Three-dimensional MDS solution based on group-averaged data.

Post-hoc pairwise comparisons (with Bonferroni correction) on distances averaged over real textures showed greater distance for US0Hz than US10Hz and US100Hz (P_{FWE} values < 0.01). For distances averaged over ultrasound conditions, post-hoc pairwise comparisons (with Bonferroni correction) revealed that the distance from aluminum resin was significantly longer than other real textures (P_{FWE} values < 0.05). Finally, the distance from sandpaper was significantly longer than soft brush and cloth (P_{FWE} values < 0.05).

Collectively, the multivariate analyses showed that amplitude modulations made ultrasound stimuli more similar to real textures and that ultrasound stimuli were rated as distinct from aluminum resin and sandpaper compared to most of the other real textures.

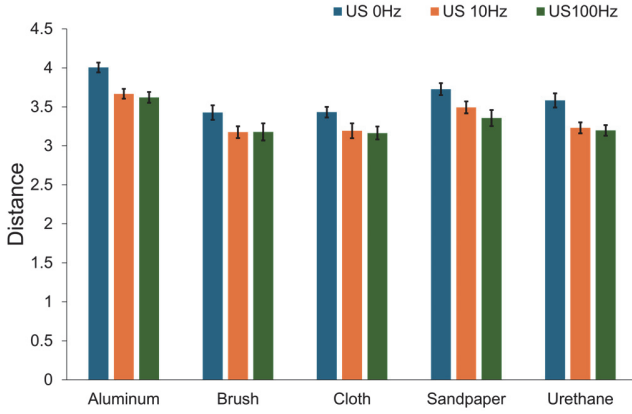


Fig. 5. Distance from real textures. Mean Mahalanobis distances from each ultrasound stimulation to the real textures are shown ($N = 29$).

C. Intraclass correlations

In the present study, participants were instructed to evaluate each stimulus in a way that ensured consistency across all blocks. A potential concern is that participants may have shifted their rating scale between blocks. If this had occurred, consistency between blocks would be low even within repeated presentations of the same type of stimulus. To examine this possibility, we calculated intraclass correlation coefficients [ICC(3,1)] between repetitions of real surfaces and between ultrasound stimuli. ICC values were 0.63 (95% confidence interval: 0.61–0.65) for real surfaces and 0.59 (95% confidence interval: 0.56–0.62) for ultrasound stimuli, indicating moderate and acceptable reliability [53].

TABLE I
QUESTIONNAIRE ON MATERIALS THAT WERE
PERCEPTUALLY SIMILAR TO ULTRASOUND
STIMULATION

Category	Number (out of 29)	%
Brush	13	44.8
Cotton	2	6.9
Needle/Electricity	4	13.8
Other materials	4	13.8
None	2	6.9
Air/Breeze	4	13.8

D. Post-Experimental Questionnaire

Table 1 shows participants' responses to the open-ended question about what material they felt had stimulated their forearm in the ultrasound stimulation conditions. The majority reported that sensations resembled real materials, such as a brush or cotton, even though they had also been exposed to other real textures during the experiment. Four participants

described the sensation as similar to a needle or static electricity, possibly due to the tingling sensations induced by the ultrasound stimuli. The "Other materials" category included responses such as "soft squishy material," "something foggy," "unknown object," and "various textures."

E. Supplementary Experiment

In the main experiment, we used a weaker force than in previous studies on brush stroking and CT fibers. One potential concern is that differences in force might lead to different patterns of perceived object properties and affective responses. To address this, we conducted a supplementary experiment examining the effect of force on brush stroking by using two levels of force: 0.03 N and 0.3 N. Fig. 6 shows the results of this supplementary experiment. We conducted a three-way mixed ANOVA (2 force levels $\times$ 4 speeds $\times$ 2 sexes) on pleasantness ratings. The analysis revealed a significant main effect of speed [$F(1.8, 48.5) = 27.4, p < 0.001, \eta_p^2 = 0.50$], while no other main effects or interactions reached significance (all p values > 0.05). Post-hoc pairwise comparisons (with Bonferroni correction) confirmed that, regardless of force, brush strokes at 3 mm/s were rated as less pleasant than those at the other speeds, and strokes at 10 mm/s were rated as less pleasant than those at 30 and 100 mm/s (P_{FWE} values < 0.05). These results indicate that the pattern of pleasantness ratings was comparable between the 0.03 N and 0.3 N conditions.

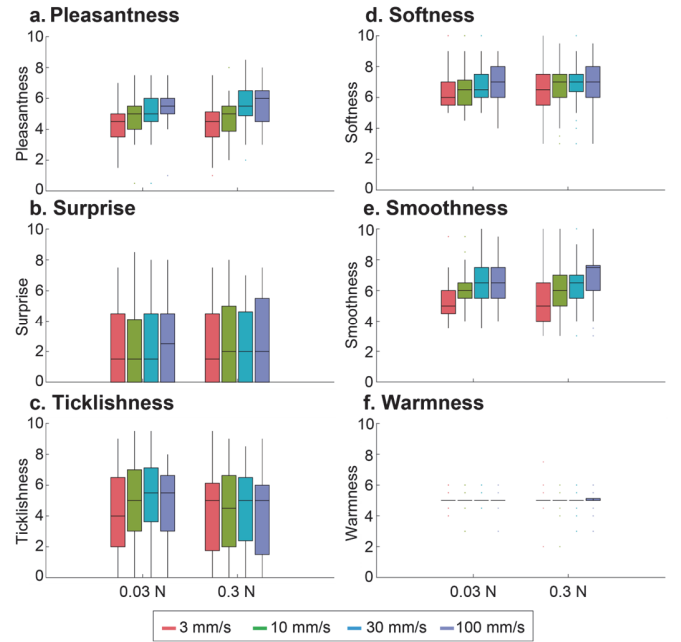


Fig. 6. Ratings from the supplementary experiment using a soft brush. Boxplots show ratings for (a) pleasantness, (b) surprise, (c) ticklishness, (d) softness, (e) smoothness, and (f) warmth. $N = 29$.

We also conducted the same three-way ANOVA on the other affective dimensions. The analysis of surprise revealed no significant effects (all p values > 0.05). In contrast, the analysis of ticklishness revealed a significant interaction between speed

and force [$F(2.6, 70.9) = 3.43, p = 0.027, \eta_p^2 = 0.113$]. Post-hoc paired t-tests with Bonferroni correction, conducted for the 0.03 N condition, showed that ticklishness ratings were significantly higher at 3 mm/s compared to 30 mm/s ($P_{FWE} = 0.036$). In contrast, no significant differences in ticklishness were found across speeds in the 0.3 N condition (P_{FWE} values > 0.9).

Finally, we conducted the same three-way ANOVA (2 force levels $\times$ 4 speeds $\times$ 2 sexes) on the three dimensions of discriminative touch. Significant main effects of speed were observed only for softness and smoothness: $F(2.1, 57.8) = 7.27, p = 0.001, \eta_p^2 = 0.212$ for softness and $F(1.8, 47.4) = 16.73, p < 0.001, \eta_p^2 = 0.383$ for smoothness. No other effect was significant ($p > 0.2$). Post-hoc pairwise comparisons (with Bonferroni correction) revealed that brush strokes at 30 mm/s were perceived as softer than those at 3 and 10 mm/s (P_{FWE} values < 0.05). For smoothness, strokes at 3 mm/s were rated as less smooth than all other speeds, and strokes at 10 mm/s were rated as less smooth than those at 100 mm/s (P_{FWE} values < 0.01). Finally, the same ANOVA on warmth showed no significant effect (p values > 0.3). These results suggest that the patterns of discriminative touch were comparable between the 0.03 N and 0.3 N conditions.

F. Supplementary nonparametric analyses

Shapiro–Wilk tests (with Bonferroni correction) revealed significant deviations from normality for warmth ratings in the main experiment and for pleasantness and warmth ratings in the supplementary experiment (P_{FWE} values < 0.05). Although ANOVA is robust to non-normality under the central limit theorem, we confirmed that non-parametric analyses yielded the same significant differences as the parametric analyses (see Supplementary Material).

IV. DISCUSSION

The main findings are threefold. First, univariate analyses showed comparable speed-dependent patterns of tactile pleasantness between ultrasound stimuli and real textures. Second, ultrasound stimuli differed from aluminum resin, sandpaper, and urethane rubber in one or more dimensions of discriminative touch, and the 10 Hz amplitude-modulated ultrasound stimulus was rated significantly more pleasant than sandpaper. Finally, multivariate analyses showed that ultrasound stimuli with amplitude modulation at 10 Hz and 100 Hz were significantly more similar to real textures than the unmodulated ultrasound stimulus (US0Hz).

A. Speed effect

In the present study, we observed a significant main effect of speed on pleasantness ratings, with no significant interactions. Pleasantness ratings were higher at speeds above 3 mm/s. This finding suggests that ultrasound stimulation can evoke speed-dependent tactile texture perception, similar to that produced by a soft brush or other real materials. Previous studies have reported similar speed-dependent patterns of pleasantness for soft brushes [12], [13] and materials such as velvet, cotton, and plastic mesh [14], [15], with higher ratings typically observed in the 10–100 mm/s range. Our results extend these findings by

demonstrating that mid-air ultrasound stimulation can also elicit similar speed-dependent change in pleasantness.

As compared to previous studies [33], [34], pleasantness ratings in the present study were sensitive to differences between 3 mm/s and higher speeds. One possible explanation is that the force applied at the focal point in the present study (approximately 30 m N) was stronger than in previous studies (e.g., 10 mN [34]). A prior study reported that lighter forces can elicit stronger ticklish sensations [39]. It is therefore possible that the greater force used in our study reduced ticklishness, thereby unmasking the differences in pleasantness between 3 mm/s and the other conditions.

Speed-dependent patterns in surprise ratings for both ultrasound and real textures showed only a trend toward significance, with higher ratings at 3 mm/s compared to 30 mm/s. Although this trend is consistent with previous studies reporting increased arousal when stroke speeds deviated from the CT-optimal range [54], [55], it did not reach significance in the present study and should be interpreted with caution.

Ticklishness ratings revealed a significant interaction among texture, speed, and sex. However, differences consistent between the two sexes were observed only for ultrasound stimulation at 10 Hz, specifically between 10 and 100 mm/s, and not for the other texture types. Previous research has shown that lighter tactile stimulation tends to elicit greater ticklishness [39]. Our findings suggest that ticklishness responses to stroking speed are modulated in a complex manner by both texture type and participant sex.

We found no consistent effect of speed on softness perception, which aligns with a previous study demonstrating perceptual constancy of softness despite different movement speeds [44]. Smoothness ratings revealed a significant texture $\times$ speed interaction; however, no speed effect was observed for the ultrasound stimuli, while brush and aluminum resin textures were sensitive to speed changes. This finding is largely consistent with previous research on roughness perception on hairy skin: perceptual constancy of roughness across speeds is maintained on glabrous skin [56] but not necessarily on hairy skin [52].

Finally, a speed-dependent effect on warmth ratings was observed for both US0Hz and cloth. Specifically, faster speeds increased perceived warmth for US0Hz, whereas the opposite pattern was found for the cloth and urethane rubber. This result suggests that different mechanisms underlie the warmth perception of ultrasound stimuli and real textures. For real textures, the degree of heat exchange at the boundary between the skin and the stimulus can increase with longer contact durations, potentially leading to a colder perception at lower speeds. In contrast, it is known that the mechanical energy of ultrasound stimulation is partially converted into heat on the surface of the skin [57]. This effect might be stronger during the longer contact duration.

B. Perceptual dimensions of discriminative touch

All mid-air ultrasound conditions were rated as different from aluminum resin, sandpaper, and urethane rubber largely across speed conditions and in one or more discriminative tactile dimensions. More specifically, aluminum was rated as harder and colder than the ultrasound stimuli, while sandpaper was perceived as rougher and harder. Urethane rubber was also

rated as colder than the most of the ultrasound stimuli. These findings, partially supported by the results of the multivariate analysis, suggest that mid-air ultrasound stimulation can evoke tactile sensations that are distinct from those produced by aluminum, sandpaper, and urethane rubber.

In contrast, we did not observe consistent differences between the ultrasound stimuli and either the brush or the cloth conditions across speeds and sexes. These results suggest that certain ultrasound conditions can elicit perceptual experiences that partially overlap with those of brush and cotton cloth stimulation.

Previous studies have compared ultrasound-based and real texture stimuli [30], [31]. In one study, ultrasound stimuli applied to the participant's palm were perceived as more similar to a brush than to a sponge or towel [30]. Another study used mid-air ultrasound to generate texture patterns and examined the similarity between real and digital textures [31], reporting differences in roughness ratings across textiles. However, other perceptual dimensions of discriminative touch were not assessed. The present study extends these findings by showing that mid-air ultrasound stimulation was partially perceived as more similar to cloth and brush than to aluminum, sandpaper, or urethane rubber. This result is in line with our hypothesis that mid-air haptics may evoke sensations resembling brush strokes. This interpretation is also consistent with post-experiment questionnaire responses, in which approximately half of the participants described the mid-air tactile stimuli as resembling the stroke of a brush or cotton.

In the present study, participants' responses in the post-experimental questionnaire may have been influenced by prior exposure to brush stimulation during the experiment. Nevertheless, because they were equally exposed to other textures, it is plausible that ultrasound stimulation was perceived as relatively more similar to a soft brush (or cotton cloth) than to the other materials.

C. Perceptual dimensions of affective touch

As hypothesized, univariate analyses showed that the US10Hz condition was rated as more pleasant than sandpaper. This finding demonstrates that ultrasound stimuli, designed to mimic soft brush strokes, can evoke greater pleasantness than some real textures. A previous study examined texture patterns generated by mid-air ultrasound [31] but found no differences in valence or arousal. The present study extends those findings by showing that ultrasound stimuli can, in some cases, elicit more pleasant sensations than real materials. No such difference was observed for aluminum resin, another control condition—possibly because the stimulation was applied with only light force, which may have mitigated the typically unpleasant sensations associated with its hardness [44] and coldness [13].

Given these rating patterns, the ultrasound stimulation used in the present study—along with stimulation from cloth and brush—might engage common neural mechanisms, particularly when compared to the control stimuli (sandpaper and aluminum resin). Hairy skin contains multiple types of afferent fibers, including CT fibers [18], [58]. Our supplementary experiment showed that brush strokes delivered at both 0.03 N and 0.3 N produced highly similar perceptual responses, except in the dimension of ticklishness. Previous research has shown that CT afferents respond to indentation forces as low as 0.3–2.5 mN of

von Frey Hair bristle (with around 0.1 mm diameter) [11]. Thus, it is reasonable to assume that both force levels used in our brush stimulation could elicit comparable neural responses. It is therefore possible that mechanoreceptors such as CT fibers were similarly activated by the ultrasound, brush, and cloth stimuli in our study. By contrast, stimulation of sandpaper involves different activity patterns of these mechanoreceptors resulting in less tactile pleasantness.

Although the effect was not consistent across speeds and sexes, the brush was perceived as more ticklish than the ultrasound stimuli under certain conditions. Stroking with feathers at low normal forces—such as 0.03 N—has been shown to induce strong ticklishness. Since brushes consist of multiple fine hairs, some of which may contact the skin with forces even lower than 0.03 N, they may elicit stronger ticklish sensations than other textures. Ticklishness evoked by very light, moving touch is known as knismesis, which is thought to serve an evolutionary role in alerting us to blood-sucking insects or skin parasites [39]. It has been hypothesized that knismesis is transmitted via fast-conducting myelinated fibers ($A\beta$ or $A\delta$), reflecting the urgency of such sensations [39]. It is therefore possible that the brush induced greater ticklishness than the ultrasound stimuli by more effectively stimulating these myelinated fibers. Furthermore, the activation of tickle-related fibers under light force stimulation may have suppressed the pleasant sensations typically mediated by CT fibers, potentially resulting in moderate levels of pleasantness across all stimuli.

D. Amplitude modulations felt closer to real textures than without amplitude modulation

In the present study, we found that amplitude-modulated ultrasound at 10 Hz and 100 Hz produced perceptual experiences that more closely resembled real textures in the multivariate analyses. Texture perception has been linked to the activity of rapidly adapting afferent fibers—Meissner and Pacinian corpuscles—in the glabrous skin of non-human primates [59]. This neural activity has been associated with perceived roughness in humans. Although the relationship between the frequency of amplitude modulation and mechanoreceptor activity is not fully understood, amplitude modulation of ultrasound stimulation may activate these mechanoreceptors in a way more similar to real texture stimulation than stimulation without amplitude modulation. On the other hand, a previous work showed that adaptation to 100 Hz vibration impaired the discrimination of fine surfaces (with spatial periods below 100 μm), whereas this effect was not clearly observed at 10 Hz [60]. These findings suggest that different mechanisms may underlie the perceptual effects of 10 Hz and 100 Hz amplitude modulation. Further research is needed to clarify why both frequencies produced similar texture perceptions in the present study.

E. Limitations and Implications for Applications of Findings

There are four limitations to this study. First, we treated rating patterns across multiple dimensions as a useful proxy for perceptual similarity. Nevertheless, this approach does not guarantee perceptual equivalence. Future studies using stricter psychophysical methods, such as point of subjective equality or forced-choice matching, will be necessary to directly assess

whether ultrasound stimuli can reproduce the same experiences as real textures.

Second, we selected 10 Hz and 100 Hz as representative components of low- and high-frequency modulation to examine their effects on tactile perception, given the lack of prior work on amplitude modulation of ultrasound. Future studies should directly measure vibration patterns on the dorsum of the hand to refine the choice of modulation frequencies.

Third, 6.5% of participants reported that the ultrasound stimulation felt like a needle. Although none of the participants reported pain, mid-air ultrasound stimuli may induce unpleasant tingling sensations. These individual differences in sensory responses should be examined in future studies. Fourth, pleasantness ratings tended to cluster around the midpoint of the scale (approximately 5), suggesting that the stimulation did not elicit strong pleasant sensations in participants. One possible explanation is the concurrent induction of knismesis which may attenuate the affective pleasantness of the stimulation. This may relate to substantial inter-individual variability in pleasantness ratings in response to brush strokes [61]. Future research should aim to identify methods for suppressing knismesis in order to enhance the pleasant aspects of tactile stimulation.

Fifth, the present study did not include movement speeds above 100 mm/s due to technical constraints. Although mechanoreceptors in hairy skin also respond to speeds greater than 3 mm/s [12], [13], their firing rates tend to increase monotonically with stroke speeds between 3 and 300 mm/s [12], [13]. Since pleasantness ratings between 30 and 100 mm/s were comparable in the present study, it is unlikely that the effects observed in our study can be attributed solely to mechanoreceptors other than CT fibers. Nevertheless, it is important to investigate stimulation at speeds exceeding 100 mm/s in future work. Finally, like previous studies [14], [15], [61], this study was based on the assumption that soft brush strokes effectively activate CT fibers. Future studies should directly examine activity of mechanoreceptors in response to mid-air ultrasound stimulation to validate this assumption [19].

While tactile displays and haptic devices using micro-actuator arrays have been developed to produce realistic surface pressures and textures on the skin, the present findings indicate that mid-air ultrasound tactile display technology can also evoke sensations partly comparable to those produced by real soft brush and cloth.

V. CONCLUSION

In conclusion, ultrasound stimulation was perceived as significantly different from aluminum resin, urethane rubber, and sandpaper in at least one dimension of discriminative touch (softness, smoothness, or warmth), while its perceptual ratings were more comparable to those of cloth and soft brush. Ultrasound stimuli with amplitude modulation at 10 Hz and 100 Hz were rated as significantly closer to real textures than unmodulated ultrasound. These findings suggest that mid-air tactile displays can evoke tactile sensations on hairy skin similar to those elicited by a soft brush stroke. Furthermore, amplitude modulation appears to be a promising technique for generating more realistic texture sensations with mid-air ultrasound tactile displays.

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