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Cutaneous Wave Propagation Shapes Tactile Motion: Evidence from Air-Coupled Ultrasound

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***Abstract*— Tactile stimulation of the skin excites cutaneous waves that travel tens of centimeters, but the implications for haptic engineering and perception are not well understood. We present evidence from optical vibrometry that tactile motion cues delivered via air-coupled ultrasound excite complex spatiotemporal wave fields in the hand. We distinguished two physical regimes based on the ratio of the motion speed to the cutaneous wave speed. At low speeds (1-4 m/s), waves generated by a moving stimulus propagated to similar distances in all directions. At high speeds (4-15 m/s), waves in the direction of motion were compressed. We also studied tactile motion perception at these speeds, which were faster than those used in prior studies. Motion sensitivity was impaired when waves were inhibited in front of the moving stimulus. This occurred for motion at high speeds and across disconnected skin areas. Together, our findings suggest that tactile motion perception is aided by waves propagating in the skin. This paper presents the first time-resolved observations of cutaneous responses to focused ultrasound, and contributes practical knowledge for the use of tactile motion and mid-air haptic feedback.**

I. INTRODUCTION

Tactile stimulation of the skin excites mechanical waves that travel tens of centimeters [1], [2]. Recent research, including work in our lab, demonstrates that these waves carry information about the tactile events that generate them [3], [4], and that they can be used to aid perception [5]. However, the implications of these processes for tactile perception are not fully understood. Recent research also suggests that the perception of spatiotemporal tactile stimuli delivered via air-coupled ultrasound may be influenced by the extent and speed of cutaneous wave propagation [6], but no prior studies have observed the complex, spatiotemporal responses in the skin that are excited by air-coupled ultrasound. Consequently, these interactions are not well understood.

Here, we measured cutaneous wave fields elicited by focused ultrasound using time-resolved optical vibrometry. We show that tactile motion delivered by air-coupled ultrasound produces complex spatiotemporal wave fields in the skin. We observe that the wave fields that are generated by a moving stimulus vary with speed. We identify a low-speed regime, in which waves propagate to similar distances in all directions from the stimulus, and a high-speed regime in which waves are compressed in the direction of motion. To clarify the perceptual relevance of these observations, we designed a behavioral experiment on tactile motion perception. We found motion discrimination to be greatly impaired when the tactile motion speed approached the wave speed, or when the motion traversed disconnected parts of the skin. In both cases, wave propagation was inhibited in front of a moving tactile stimulus.

A. Cutaneous Waves and Air-Coupled Ultrasound

Touch sensation arises from mechanical strains that are captured by numerous cutaneous mechanoreceptors. Tactile stimulation generates mechanical waves that propagate to distances of tens of centimeters in soft tissues, exciting widespread tactile afferents [1], [2], [3]. At vibrotactile frequencies, transmission occurs via transverse shear waves and boundary (e.g. Rayleigh) waves. They travel at frequency-dependent speeds that are low ($c < 25$ m/s in glabrous skin) relative to acoustic (compression) waves ($c > 1400$ m/s). Viscoelasticity causes soft tissues to be dispersive, with frequency-dependent wave speeds, and imparts damping. The latter causes vibrotactile signals in the skin to decay within a few tens of milliseconds [3], [7].

Ultrasound phased arrays comprise collections of ultrasonic transducers that are driven to constructively interfere, creating high pressure foci in air, sufficient to deliver small indentations to the skin [8], [9], [10]. The focused stimuli can be modulated in amplitude or space to dynamically excite the skin via acoustic reflection [11], stimulating vibration-sensitive mechanoreceptors.

Waves in the skin appear to affect the perception of such focused ultrasound stimuli [6]. Frier et al. used non-contact vibrometry to demonstrate that skin responses to a moving focal point depended on the speed of translation. This appeared to be due to mechanical waves excited in the skin. The speed of the moving focus relative to the cutaneous wave speed appeared to affect the perceived intensity of the stimuli. However, a detailed explanation was unclear, in part, because the evolution of the wave fields in the skin could not not be directly observed.

Here, we report the first time-resolved observations of cutaneous wave fields induced by air-coupled ultrasound. We use the results to clarify the relationship between the continuum mechanical response of the skin and tactile motion perception.

B. Tactile Motion Perception

Manual activities commonly involve the motion of objects against the skin, exciting spatiotemporal patterns of activation in populations of sensory mechanoreceptors. These activations are integrated by the brain, yielding motion

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percepts [12]. Tactile motion cues comprise stimuli that move continuously along the skin [13], [14], [15]. Such cues may also be simulated by stimulating the skin at an array of discrete locations [16], [17]. Sensitivity to discrete motion cues is lower than for continuous motion [18]. Tactile motion cues may also be delivered without solid contact via focused fluids, including liquid [19] or air [9], [20], [21]. The latter can be controlled through air-coupled ultrasound phased arrays [6], [9], [21], reproducing arbitrary motion paths with different speeds.

Here, we use focused ultrasound to produce motion cues with speeds from 0.5 to 15 m/s. These speeds are higher than those used in all prior studies of tactile motion perception that we are aware of. We show that motion perception becomes greatly impaired at the highest speeds in this range. We present evidence that this occurs at speeds comparable to the propagation speeds of cutaneous waves.

II. CUTANEOUS WAVES EXCITED VIA TACTILE MOTION

In a first experiment, we assessed the response of the skin in the volar hand surface to tactile motion delivered via focused ultrasound. Motion occurred proximally or distally along digit 2 at speeds ranging from 1 to 15 m/s. The skin response was captured via optical vibrometry. We hypothesized that skin responses would reflect wave propagation in the skin.

A. Participants

Measurements were captured from the hand of one human participant (age 24, male). In order to verify that these data were not anomalous, we captured additional data from two further participants (ages 24 and 27, both male) in a subset of conditions, with similar results. Participants gave their written, informed consent. The experiment was conducted according to the protocol approved by the Human Subjects Committee of the University of California, Santa Barbara.

B. Apparatus and Stimuli

Skin vibrations were captured using a non-contact scanning laser doppler vibrometer (SLDV, model PSV-500, Polytec, Inc., Irvine, CA). The sampling frequency of the measurements was 125 kHz. The hand was located within the field of view of the SLDV. It was stabilized in an open posture using five custom 3D printed brackets affixed to the fingernails via adhesive tape (Fig. 1A). The arm, hand, and brackets were supported by a vibration-isolated optical table. Participants were seated in a reclined chair raised to a height at which the arm was relaxed.

An ultrasound phased array (UHEV1, Ultrahaptics, Ltd.) stimulated the skin at focal points that were controlled to move across the volar hand surface. The device comprised 256 ultrasonic transducers arranged in a 16x16 grid. The carrier frequency was 40 kHz, yielding a focal point approximately 1 cm in diameter, which was within diffraction limits for air (at 40 kHz, $\lambda/2 \approx 0.4$ cm). The position and power of the focal point were updated at a rate of 16 kHz using focus control software (Ultrahaptics SDK). To avoid occluding the hand from the SLDV, the ultrasound device was positioned at an angle of 45 degrees from the volar hand surface, with a mean distance of 30 cm from the hand (Fig. 1A). We compensated for the oblique angle with the control software.

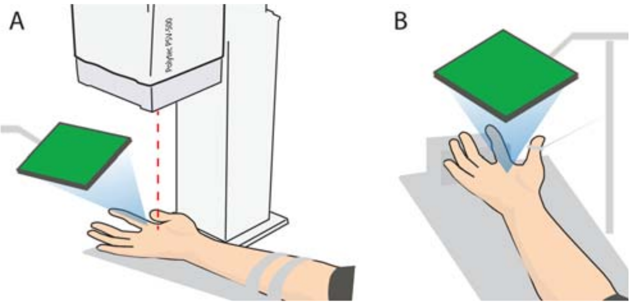

Fig. 1: A) In the mechanical experiments, focused ultrasound delivered tactile motion cues along the proximal-distal axis of digit II. Skin vibrations were captured via optical vibrometry. B) We assessed the perception of tactile motion on the proximal-distal axis and a leftward-rightward axis across the fingers.

The stimuli were moving ultrasound focal points that were swept once across the volar hand surface, along the axis of digit 2. Motion occurred at one of six speeds: 1, 2, 4, 7, 11, or 15 m/s. Motion paths were approximately 10 cm long, and extended from the proximal base of the thenar eminence to the distal end of digit 2, or vice-versa (Fig. 2A). The paths were registered to the size and shape of the hand.

To aid comparisons of the measurements with results from the perception experiment (Section 3 below), we applied spatiotemporal modulation to the motion paths [6], with amplitude 20 mm transverse to the nominal motion direction (i.e. a zig-zag motion), frequency 62.5 Hz (Fig. 2B), and focal point intensity set to the maximum allowed by the control software. This ensured that the stimulus could be felt at both slow and fast motion speeds.

Capturing spatially- and temporally-resolved waves in the skin required accurate synchronization across all of the sequentially-captured measurement points. To achieve this, a hardware trigger signal was taken from the ultrasound device and used to initiate data capture and calibration by the SLDV for each measurement point.

C. Procedure

After the participant was positioned at the apparatus, a 3D scan of the volar hand surface was performed via the integrated geometry scanner of the SLDV. The SLDV measured the velocity of skin motion normal to the volar hand surface during the experiment. The 300 measurement points were equally distributed across the hand surface. Two complete spatiotemporal scans were captured at each of the six speeds and in each direction. The six speeds, two directions, two repetitions, and 300 measurement locations yielded 7200 discrete measurements of approximately 30000 samples each. Accounting for re-measurement, this required four hours of measurement time in total.

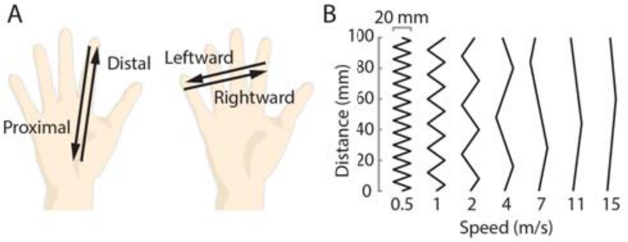

Fig. 2: A) Tactile motion stimuli moved across the volar hand surface in four directions. B) The spatial position transverse to the motion direction was modulated at 62.5 Hz, yielding the paths shown.

D. Analysis

For each trial, the data consisted of the recorded skin velocity, $v(t)$ normal to the volar hand surface at each of 300 measurement points. Because of the small amplitude of the ultrasound-excited signal in the skin, we removed less than 10% of the data points for which the SLDV signal quality was low. We analyzed the data in several frequency bands, including a range from 40 to 240 Hz that corresponded to a range of high vibrotactile sensitivity and large signal energy. We spatially interpolated the measurements at intermediate positions using physiologically-informed distance weighting as described in our earlier paper [3]. We analyzed the temporal frequency content at select locations by computing Fourier transforms, $V(f)$.

E. Results

The results consist of spatially- and temporally-dependent skin vibration velocity, $v(x,t)$, normal to the volar hand surface that was elicited by focal points moving at different speeds (Fig. 3). At low speeds, the dominant frequency of temporal oscillation at different points on the volar hand surface matched the expected excitation frequency (125 Hz) due to the spatially oscillating motion of the stimulus (Fig. 3C). At high speeds, the motion path barely undulated during a complete trajectory across the hand (Fig. 2B), yielding a transient signal in the skin with a decaying frequency response (Fig. 3C).

Spatiotemporal reconstructions of the skin vibrations revealed that the 0.8 cm^2 ultrasound focal point excited the largest amplitude skin vibrations ($v \approx 0.1$ mm/s) in a region of about the same size. These vibrations propagated in an oscillating manner far into surrounding tissues. The spatial propagation patterns varied with the focus location. Lower amplitude vibrations were excited near the base of digit 2. Higher amplitude vibrations were produced near the proximal phalanx of digit 2, just 2-3 centimeters away. These differences may reflect effects of skin dynamics and variations in local skin geometry and mechanics.

The spatial and temporal patterns of skin vibration also varied with the tactile motion speed. At low speeds, less than 4 m/s, waves originating at the focal point propagated outward, reaching distances of ten or more centimeters in each direction. These wave patterns differed from those produced at higher speeds. Published measurements suggest that the tactile stimuli in this experiment excited cutaneous waves with speeds between 5 and 20 m/s [7]. The fastest motion speeds we tested, 11 to 15 m/s, were well within this range. At these speeds, waves propagating in the direction of motion remained near (< 1 cm) to the focus, suggesting a Doppler effect, as would be expected from wave mechanics. Consequently, at such speeds, the moving focus traversed skin locations less than 1 ms after the first arriving waves. Waves travelling opposite the high-speed motion extended even farther from the focus than they did in the low-speed case, reaching tens of centimeters.

III. EXPERIMENT: TACTILE MOTION PERCEPTION

Our observations of cutaneous responses to ultrasound-generated tactile motion stimuli suggested that distinct patterns of skin responses were generated as the motion speed approached the propagation speed of cutaneous waves. Informed by this, and by a prior study that suggested that the perception of such stimuli varied with motion speed [6], we hypothesized that the transmission of propagating waves from the focal point could contribute to motion perception. We further hypothesized that motion perception would be impaired at high speeds, due to the spatially and temporally shorter extent of waves in the direction of motion. We evaluated these ideas in an experiment in which participants reported the direction of tactile motion at different speeds along the same proximal-distal axis studied in the vibrometry experiment, and along another, rightward-leftward axis, that crossed disconnected regions of skin that interrupted wave transmission along the motion path.

A. Participants

Twelve participants volunteered for the experiment (ages 19-28, 6 female and 6 male). None reported any disorder affecting sensation in the hand. Participants gave their written, informed consent. The experiment was approved by the Human Subjects Committee of the University of California, Santa Barbara.

B. Apparatus and Stimuli

The apparatus (Fig. 1) was nearly identical to the one used in the vibrometry measurements, except that the vibrometer was absent. Participants were seated and with their hand supported on a foam surface and the forearm supported by an armrest (Fig. 1B). The volar hand surface faced upward, 15 cm beneath the ultrasound display. The fingertips were separated by 1 cm. The hand was held in place via double-sided tape on the dorsal side.

The ultrasound device produced tactile motion stimuli during the experiment. The focal distance was calibrated to lie at the distance of the volar hand surface. Motion occurred in one of four directions: distal, proximal, rightward, or leftward (Fig. 2). The proximal and distal trajectories matched those used in the vibrometry experiment. The leftward and rightward trajectories were added in order to introduce stimuli for which vibration-elicited waves were prevented

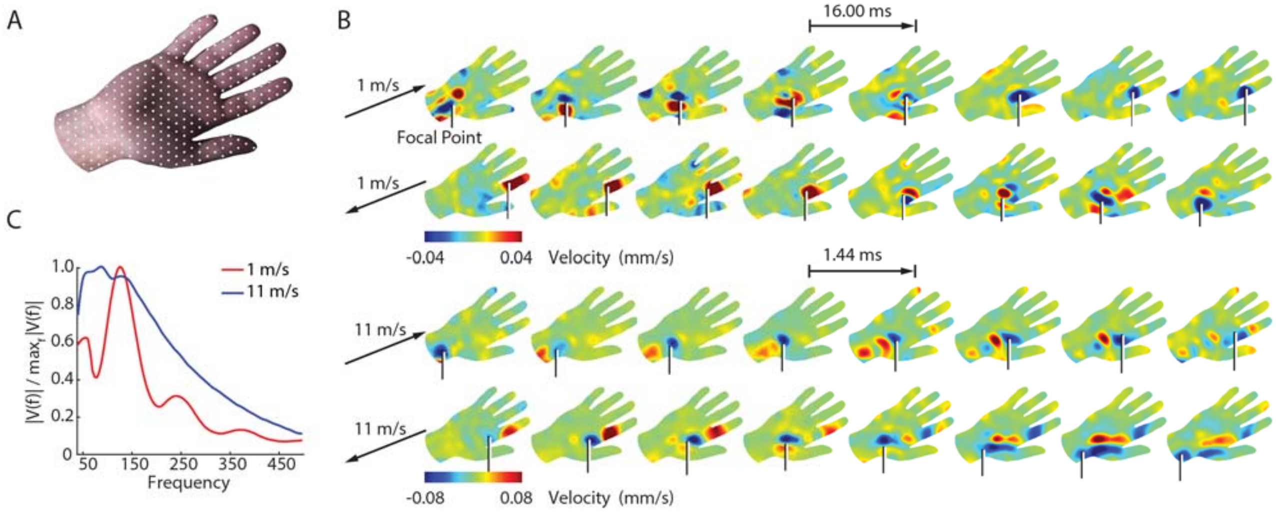

Fig. 3: A) Measurement locations on hand surface for the vibrometry experiments. B) Time-resolved velocity of skin vibrations across hand during tactile motion. Low speeds elicited propagation patterns that radiated outward in all direction from the focal point, while high speeds elicited patterns that trailed behind the focal point. C) Normalized magnitude spectrum of skin velocity averaged across all measurement points along the path of motion. Low speeds excited skin vibrations at 125 Hz and harmonic multiples thereof; high speeds excited broadband frequency content.

from propagating along the direction of motion, due to the gaps between the fingers.

Each focal point moved at one of six different speeds: 0.5, 1, 2, 4, 7, and 11 m/s. These speeds overlapped those used in the vibrometry measurements, but were somewhat lower, because it became clear from pilot testing that the direction of motion could not be discerned at higher speeds. Participants wore earplugs (attenuation rating 33 dB) and circumaural headphones playing pink noise to mask auditory cues.

C. *Procedure*

During each trial of the experiment, participants judged the direction of tactile motion in a two-alternative forced choice task. One of the alternatives was the direction of motion and the other was the opposite direction. Participants were free to play each stimulus as many times as they preferred before responding. Responses were collected via the graphical user interface of a computer by selecting from one of two visual representations of the tactile motion directions (Fig. 2A). The experiment was block randomized, with each block composed of a random permutation of all speeds and directions, yielding 24 trials per block. Each of the six speeds and four directions was presented 10 times, producing a total of 240 trials per participant. Prior to the experiment, participants felt each stimulus used in the experiment once, but were not informed of the directions of motion. Following the experiment, participants completed a questionnaire that asked them to report the differences between the stimuli, the number of distinct stimuli in each direction, and indicate where sensations were localized on the hand.

D. *Analysis*

The data consisted of a binary response for each trial indicating whether the identified motion direction was correct or incorrect. Chance performance corresponded to 50%. We grouped the proximal and distal, and rightward and leftward, directions in the main analysis. We separated each direction pair in a subsequent analysis in order to assess asymmetries in direction discrimination.

We analyzed the response data using Generalized Linear Mixed Models (GLM) with a logistic link function, $y = \log(\frac{\mu}{1-\mu})$, where μ was the proportion of correct responses. In the analyses, direction and speed (and their interaction) were treated as fixed effects and participants as random effects. Statistical significance was determined using a maximum likelihood test. We also computed the proportion of correct responses in each condition and fit a psychometric function of the form $\psi(x;\alpha,\beta) = 0.5(1+F(x;\alpha,\beta))$, where F was the Weibull function [22]. We combined the collected responses from all participants in order to analyze changes in tactile motion discrimination performance with speed and direction.

E. *Results*

Every participant correctly identified the motion direction at greater than chance levels at the lowest speed, 0.5 m/s (Fig. 4). For both the distal-proximal and rightward-leftward axes, the mean proportion of correct responses decreased monotonically with increasing speed, and converged to chance levels at 7 m/s and 4 m/s, respectively, and remained so for the highest speed of 11 m/s.

On average, participants were able to more accurately report distal-proximal motion than rightward-leftward motion. The GLM analysis revealed significant differences between the perception of distal-proximal and rightward-leftward motion ($p < 0.0001$). Across all directions, accuracy significantly decreased with increasing speed ($p < 0.0001$). We found a significant ($p < 0.0001$) interaction between speed and the motion axis (i.e. distal-proximal vs. rightward-

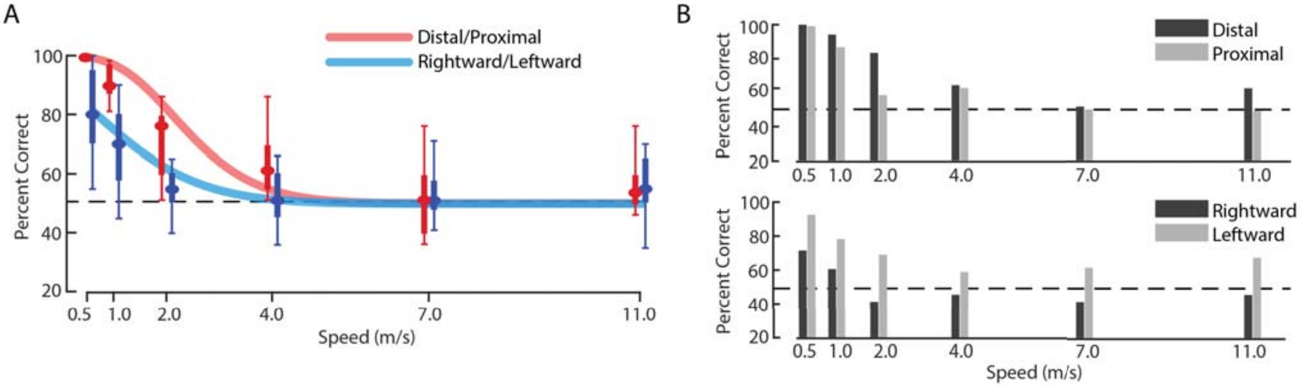

Fig. 4: A) Participants correctly identified the direction of motion more frequently at low speeds than at high speeds for motion along both the distal-proximal and rightward-leftward axes. The proportion of correct responses decreased with increasing speed. B) For both axes, there were asymmetries in motion perception, reflecting better performance in the distal versus proximal direction and in the leftward versus rightward direction.

leftward), indicating that increasing speed yielded different rates of deterioration in motion perception for each axis, consistent with the appearance of the data (Fig. 4). For rightward-leftward motion, performance was imperfect even at the slowest speed, 0.5 m/s, which explains the more gradual decrease in motion discrimination that occured with increasing speed. There was a statistically significant effect of the participant on motion discrimination ($p = .0269$), indicating that differences between participants were predictive of motion discrimination.

Motion perception in the distal direction was significantly better than in the proximal direction ($p = 0.0058$), and was also significantly better in the leftward than the rightward direction ($p < 0.0001$), suggesting an asymmetry in sensitivity to tactile motion. In both analyses, the effect of speed was significant ($p < 0.00011$), but the interaction between speed and direction was not. There was a significant effect of the participant on the results (distal-proximal: $p = 0.016$, rightward-leftward: $p = 0.047$).

IV. DISCUSSION

The results of the vibrometry experiment revealed that tactile motion produced via air-coupled ultrasound elicited complex wave fields in the skin, which were generated by the moving focal point. The patterns varied with the speed of motion. At high speeds (> 4 m/s), on the order of the cutaneous wave speed, waves generated at the stimulus were greatly compressed in the direction of motion, reflecting a Doppler effect, as expected from wave mechanics.

Based on these results we hypothesized that the perception of tactile motion would be impaired for high-speed tactile motion. Results of the perception experiment indicated that the perception of tactile motion direction was impaired for motion speeds 4 m/s or higher, matching the high speed conditions in the vibrometry experiment. Tactile motion perception was impaired at high speeds, reaching chance levels for speeds greater than 4 m/s in all conditions. In addition, motion perception along a rightward-leftward axis was lower than along a distal-proximal axis. We also observed asymmetries in motion perception for motion along both axes, but most prominently along the rightward-leftward axis. This may merit future research.

Together, the impairment of direction discrimination that we observed at high speeds and for rightward-leftward motion indicate that the perception of tactile motion direction was impaired when waves were inhibited from propagating in the direction of motion. This is consistent with our hypothesis that cutaneous waves leading the moving stimulus contribute to tactile motion perception. However, other hypotheses could also explain the results. PC afferents (terminating in Pacinian corpuscles) are thought to play a major role in the encoding of skin vibrations. Such afferents exhibit spatially and temporally integrative responses [23]. The higher speed stimuli excited the skin for shorter durations, which could also contribute to the observed impairment of motion discrimination at such speeds. Most prior studies that have studied tactile motion perception using a localized stimulus moving on the skin employed lower speeds than were studied here, but some of these studies reported impairments in perception with increasing speed. For example, Shimizu and Wake reported that sensitivities to motion direction declined by about 50% as speed increased from 0.032 to 0.064 m/s [18], but the stimulus path distance in that study was on the order of 1 cm, much shorter than the paths used here. In addition, in our experiment, rightward-leftward motion excited similar regions of skin but crossed different hand areas and traversed a smaller region of skin than the distal-proximal stimuli did. The difference we observed in those cases could reflect anatomical or neural processing differences arising from this. However, the high performance achieved in all conditions at low speeds, and the interacting effects of motion axis and speed, may suggest that sensory input from different fingers was integrated consistently across all conditions.

V. CONCLUSIONS

Tactile stimulation excites prominent waves in the skin, but the implications for haptic engineering and perception are not well understood. In this work, we presented the first time-resolved observations of cutaneous wave fields generated by air-coupled ultrasound. The results show how tactile motion produced via focused ultrasound excites complex wave field in the skin that vary with motion speed. Different wave patterns emerged in two regimes, which we associated with the ratio of the motion speed and wave speed. During low speed motion (< 4 m/s), cutaneous waves propagated outward yielding similar wave patterns in all directions. During high speed motion (> 4 m/s), waves propagating in the direction of motion were compressed, and were confined near to the stimulus, suggesting a Doppler effect. Waves travelling opposite the high speed motion extended farther from the stimulus than they did in the low speed case. These effects are consistent with wave mechanics. The results also suggest that the patterns of such waves vary with local differences in skin geometry and mechanics.

To assess the perceptual relevance of these results, we presented a study on tactile motion perception over this range of motion speeds. These speeds were faster than those used in previous studies. We found that tactile motion perception was impaired when waves emitted in the direction of motion were inhibited. This occurred at high speeds, when waves travelling ahead of the stimulus were compressed, and for motion that crossed disconnected skin regions. Tactile motion acuity decreased with increasing motion speeds, reaching chance levels for speeds greater than 4 m/s.

Despite the informative nature of the results, several issues merit further investigation. First, the physics coupling focused ultrasound in air with cutaneous waves has not been well characterized to date. Further research is needed in order to clarify these processes. Second, although the experiments were carefully controlled, stimuli delivered by focused ultrasound are sensitive to the conditions in which they are applied, including variations in hand geometry. Third, although we report correlations between waves excited in the skin, motion speed, and tactile motion perception, further work is needed to confirm a causal relationship. The perceptual results could be affected by other anatomical or neural processing factors.

Nonetheless, we argue that the simplest explanation consistent with the vibrometry measurements, perceptual results, and a prior study of the speed-dependence of similar motion cues [6], is that tactile motion perception is aided by propagating waves in the skin that precede the motion of a stimulus. Our findings demonstrate how the mechanics of waves in the skin affects the perception of air-coupled ultrasound, and can inform the design of tactile motion and ultrasound stimuli. The results may aid future applications in virtual and augmented reality, and other areas of human-computer interaction.

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REFERENCES

[1] T. J. Moore, “A survey of the mechanical characteristics of skin and tissue in response to vibratory stimulation,” *IEEE Transactions on Man-Machine Systems*, vol. 11, no. 1, pp. 79–84, 1970.

[2] R. S. Johansson, U. Landstrom, and R. Lundstrom, “Responses of mechanoreceptive afferent units in the glabrous skin of the human hand to sinusoidal skin displacements,” *Brain Res*, vol. 244, no. 1, 1982.

[3] Y. Shao, V. Hayward, and Y. Visell, “Spatial patterns of cutaneous vibration during whole-hand haptic interactions,” *Proceedings of the National Academy of Sciences*, vol. 113, no. 15, pp. 4188–4193, 2016.

[4] L. R. Manfredi, H. P. Saal, K. J. Brown, M. C. Zielinski, J. F. Dammann III, V. S. Polashock, and S. J. Bensmaia, “Natural scenes in tactile texture,” *J. Neurophy.*, vol. 111, no. 9, pp. 1792–1802, 2014.

[5] B. Delhaye, V. Hayward, P. Lefèvre, and J.-L. Thonnard, “Texture-induced vibrations in the forearm during tactile exploration,” *Frontiers in behavioral neuroscience*, vol. 6, p. 37, 2012.

[6] W. Frier, D. Ablart, J. Chilles, B. Long, M. Giordano, M. Obrist, and S. Subramanian, “Using spatiotemporal modulation to draw tactile patterns in mid-air,” in *Intl. Conf. on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, 2018, pp. 270–281.

[7] L. R. Manfredi, A. T. Baker, D. O. Elias, J. F. Dammann III, M. C. Zielinski, V. S. Polashock, and S. J. Bensmaia, “The effect of surface wave propagation on neural responses to vibration in primate glabrous skin,” *PLoS One*, vol. 7, no. 2, p. e31203, 2012.

[8] T. Carter, S. A. Seah, B. Long, B. Drinkwater, and S. Subramanian, “Ultrahaptics: multi-point mid-air haptic feedback for touch surfaces,” in *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, 2013, pp. 505–514.

[9] G. Wilson, T. Carter, S. Subramanian, and S. A. Brewster, “Perception of ultrasonic haptic feedback on the hand: localisation and apparent motion,” in *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. ACM, 2014, pp. 1133–1142.

[10] D. Spelmezan, R. M. González, and S. Subramanian, “Skinhaptics: Ultrasound focused in the hand creates tactile sensations,” in *Haptics Symposium (HAPTICS), 2016 IEEE*. IEEE, 2016, pp. 98–105.

[11] M. Settnes and H. Bruus, “Forces acting on a small particle in an acoustical field in a viscous fluid,” *Physical Review E*, vol. 85, no. 1, p. 016327, 2012.

[12] Y.-C. Pei and S. J. Bensmaia, “The neural basis of tactile motion perception,” *J. Neurophysiol.*, vol. 112, no. 12, pp. 3023–3032, 2014.

[13] G. K. Essick and B. Whitsel, “Assessment of the capacity of human subjects and si neurons to distinguish opposing directions of stimulus motion across the skin,” *Brain Res. Rev.*, vol. 10, no. 3, 1985.

[14] D. Dreyer, M. Hollins, and B. Whitsel, “Factors influencing cutaneous directional sensitivity.” *Sensory Proc.*, vol. 2, no. 2, pp. 71–79, 1978.

[15] N. Langford, R. J. Hall, and R. A. Monty, “Cutaneous perception of a track produced by a moving point across the skin.” *Journal of experimental psychology*, vol. 97, no. 1, p. 59, 1973.

[16] C. E. Sherrick and R. Rogers, “Apparent haptic movement,” *Perception & Psychophysics*, vol. 1, no. 3, pp. 175–180, 1966.

[17] J. H. Kirman, “Tactile apparent movement: The effects of interstimulus onset interval and stimulus duration,” *Perception & Psychophysics*, vol. 15, no. 1, pp. 1–6, 1974.

[18] Y. Shimizu and T. Wake, “Tactile sensitivity to two types of stimulation: Continuous and discrete shifting of a point stimulus,” *Perceptual and motor skills*, vol. 54, no. 3_suppl, pp. 1111–1118, 1982.

[19] J. M. Loomis and C. C. Collins, “Sensitivity to shifts of a point stimulus: An instance of tactile hyperacuity,” *Perception & Psychophysics*, vol. 24, no. 6, pp. 487–492, 1978.

[20] Y. Suzuki and M. Kobayashi, “Air jet driven force feedback in virtual reality,” *IEEE Comp. Graph. App.*, vol. 25, no. 1, pp. 44–47, 2005.

[21] T. Iwamoto and H. Shinoda, “Ultrasound tactile display for stress field reproduction-examination of non-vibratory tactile apparent movement,” in *Eurohaptics Conference, 2005 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. World Haptics 2005. First Joint*. IEEE, 2005, pp. 220–228.

[22] F. A. Wichmann and N. J. Hill, “The psychometric function: I. fitting, sampling, and goodness of fit,” *Perception & psychophysics*, vol. 63, no. 8, pp. 1293–1313, 2001.

[23] M. Morioka and M. J. Griffin, “Thresholds for the perception of hand-transmitted vibration: Dependence on contact area and contact location,” *Somatosensory & motor research*, vol. 22, no. 4, pp. 281–297, 2005.