Fingertip Wearable High-resolution Electrohydraulic Interface for Multimodal Haptics

Purnendu
Reality Labs Research, Meta
ATLAS Institute, University of Colorado, Boulder
Boulder, Colorado, USA
purnendu@colorado.edu

Jess Hartcher-O'Brien
Reality Labs Research, Meta
Redmond, Washington, USA
jesshartcher@meta.com

Vatsal Mehta
Reality Labs Research, Meta
Redmond, Washington, USA
vatmehta@meta.com

Nicholas Colonnese
Reality Labs Research, Meta
Redmond, Washington, USA
ncolonnese@meta.com

Aakar Gupta
Reality Labs Research, Meta
Redmond, Washington, USA
aakar.hci@gmail.com

Carson J. Bruns
ATLAS Institute, University of Colorado, Boulder
Boulder, Colorado, USA
Carson.Bruns@colorado.edu

Priyanshu Agarwal
Reality Labs Research, Meta
Redmond, Washington, USA
pagarwal18@meta.com

2023 IEEE World Haptics Conference (WHC) | 979-8-3503-9993-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/WHC56415.2023.10224383

***Abstract*—Fingertips are one of the most sensitive regions of the human body and provide a means to dexterously interact with the physical world. To recreate this sense of physical touch in a virtual or augmented reality (VR/AR), high-resolution haptic interfaces that can render rich tactile information are needed. In this paper, we present a wearable electrohydraulic haptic interface that can produce high-fidelity multimodal haptic feedback at the fingertips. This novel hardware can generate high intensity fine tactile pressure (up to 34 kPa) as well as wide range of vibrations (up to 700 Hz) through 16 individually controlled electrohydraulic bubble actuators. To achieve such a high intensity multimodal haptic feedback at such a high density (16 bubbles/cm^2) at the fingertip using an electrohydraulic haptic interface , we integrated a stretchable substrate with a novel dielectric film and developed a design architecture wherein the dielectric fluid is stored at the back of the fingertip. We physically characterize the static and dynamic behavior of the device. In addition, we conduct psychophysical characterization of the device through a set of user studies. This electrohydraulic interface demonstrates a new way to design and develop high-resolution multimodal haptic systems at the fingertips for AR/VR environments.**

***Index Terms*—Haptic rendering, Soft Electrohydraulic Actuators.**

I. INTRODUCTION

Fingertips are the primary agents of human interaction with the physical world. We use them extensively for tapping, grasping and probing the environment. They help us explore a rich variety of haptic information like textures, sliding and contact to shape (curvature), size and stiffness (hardness/softness). No wonder, they are the most sensitive region of the human hand [1]. The high density of sensitive mechanoreceptors in the fingertips gives them a spatial tactile resolution in the sub-millimeter range (in the absence of movement or applied vibrations) [2], [3]. The threshold for tiniest feature detection in dynamic touch (presence of movement and vibrations) can be as small as 300 nm [4], [5]. Furthermore, fingertips can also sense a large range of forces (both normal and shear) [6]. In addition, coarse features (e.g., a braille cell) are encoded with spatially distributed signals, while fine textures (e.g., fine-grit sandpaper) are encoded by temporal frequencies [7].

This work was performed at the Reality Labs Research at Meta Platforms Inc.

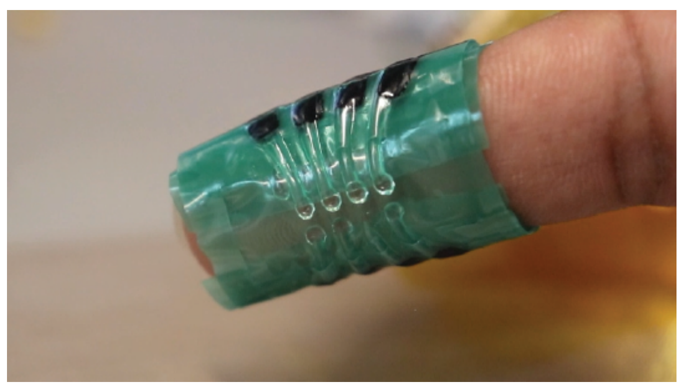

Fig. 1. The high-resolution ElectroHydraulic Haptic Interface worn over fingertip. It consists of 16 individually controlled miniaturized electrohydraulic bubble actuators capable of rendering high intensity fine-tactile pressure (up to 34 kPa) as well as wide bandwidth vibrotactile feedback (up to 700 Hz) within 1 cm^2.

This sensitivity of fingertips has attracted efforts to augment them with sensation of touch for virtual and augmented reality systems. However, the lack of wearable haptic interfaces capable of generating the required stimulus (pressure, contact, vibration etc.) prevents us from fully utilizing the sense of touch in mixed reality. Traditionally, systems based on rigid electromechanical actuators have been developed to render a variety of haptic feedback [12], [14]. Though they can generate a wide range of forces to augment the tactile sensation, attaching external rigid devices on fingertips is cumbersome,

TABLE I

A SUMMARY OF THE EXISTING FINGERTIP WEARABLE HAPTIC INTERFACES THAT EXISTS IN THE LITERATURE AND HOW THIS WORK CONTRIBUTES TO THE STATE-OF-THE-ART. HERE, FTP = FINE TACTILE PRESSURE (MORE THAN 4 PRESSURE POINTS PER CM^2); CTP = COARSE TACTILE PRESSURE (SINGLE LARGE ACTUATOR ON FINGERTIP); AND VT = VIBROTACTILE.

	Form-Factor	Power Source	Spatial Tactile Resolution	Number of Actuators	Haptic Stimuli FTP	Haptic Stimuli CTP	Haptic Stimuli VT
Our work, 2022	Fingertip	Electrohydraulic	High	16	✓	✓	✓
Han [8], 2020	Surface Display	Electrohydraulic	High	6	✓		✓
Leroy [9], 2020	Arm	Electrohydraulic	Low	25		✓	✓
Han [10], 2020	Fingertip	Fluidic	Low	1			
Han [11], 2018	Fingertip	Fluidic	Low	1		✓	
Teng [12], 2021	Fingertip	ERM	Low	1	✓		
Ujitoko [13], 2020	Fingertip	Pneumatic	High	128	✓		

given their form factor. Moreover, they cannot be miniaturized to provide high-density haptic feedback due to their limited force-density [15].

An alternative to rigid electromechanical systems are soft fluidic actuation technologies [16]. They are easy to attach to the fingertips and conform along the organic edges of the finger [17]. However, traditional fluidic actuators require an external pressure source (pumps) and arrangement of tubes and electromechanical valves to transport and control the fluid, which limits the actuation bandwidth of the system and makes it difficult to render high-frequency vibration. Further fluidic pumps are noisy, inefficient and bulky, which makes it difficult to achieve a portable and untethered wearable system.

Dielectric elastomers [17], [18] and ionic polymer actuators [19] offer another compact soft alternative, that are capable of direct electric actuation. Unlike traditional hydraulic actuators, they are fast and compact, but their implementation into a high density actuator array for fingertip is challenging and therefore, yet to be demonstrated [20]–[22]. Recently soft electrohydraulic actuators [23]–[27] are developed that offer a great alternative for soft, high performance and compact actuation technology. These soft actuators combine the benefits of fluid based actuators with electroactive polymer actuators. They store the fluid locally and can achieve high frequency actuation. Though they have been explored for haptic displays, [8], [9], a high-fidelity wearable haptic interface for the fingertip has not been explored. Table I demonstrates the state of the art related work in comparison to this work.

In order to bring a convincing sense of touch into mixed reality, the actuation technologies need to match the tactile sensitivity and resolution of the fingertips. This requires integration of high-density soft actuators with multimodal actuation capability (ability to render a variety of forces as well as vibrations) in a wearable form factor. At the same time such an interface must provide minimum encumbrance for the day-to-day activities of the hand. The ideal actuation technology should be on-skin, thin, lightweight, high-resolution, capable of multimodal feedback. Though there has been progress made across dielectric elastomers, soft electrohydraulic actuators and ionic polymers, a high-fidelity wearable haptic interface capable of bringing this vision to reality has not been demonstrated. To address this gap, we present a thin, lightweight, on-skin novel electrohydraulic haptic interface that can render high-density multimodal (fine tactile pressure and vibrations)

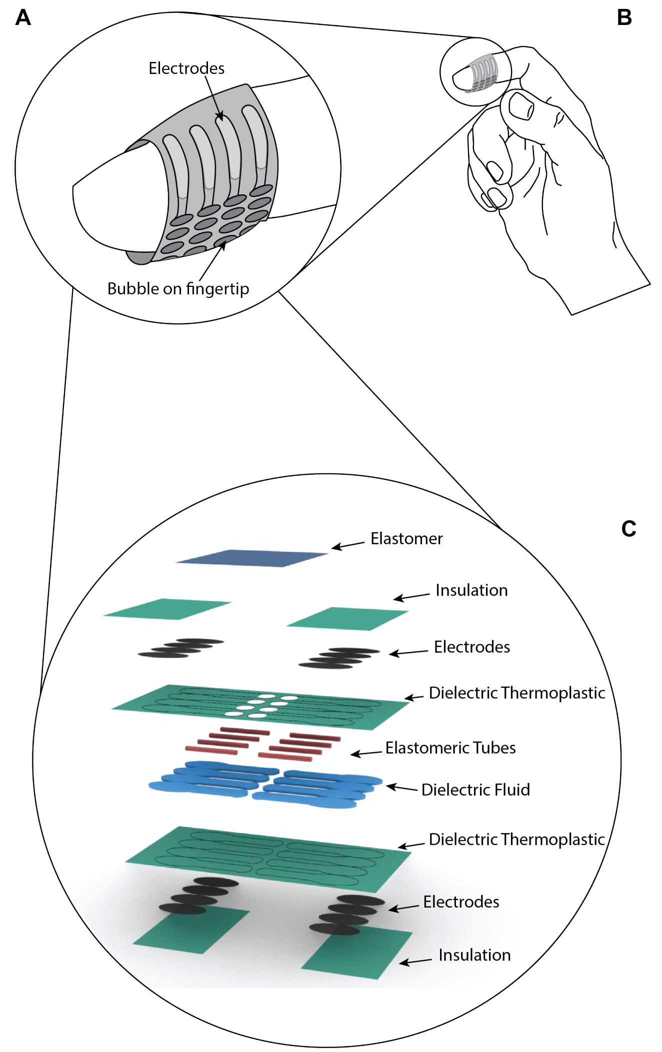

Fig. 2. Construction of the fingertip wearable ElectroHydraulic Haptic Interface. Part (A) shows detailed view over the fingertip while part (B) shows the zoomed out view to give an estimate of size. The design of these soft electrohydraulic interface consists of 16 actuators that are fabricated in two separate layers. Each layer holds 8 actuators entirely insulated from each other. Part (C) shows exploded view of all the components that go into the construction of a single layer of 8 bubble actuators.

tactile sensations on the fingertip. The interface weights < 2 grams, has a thickness of $200\mu m$, tactile resolution of 16 bubbles/cm^2 and consists of 16 individually controlled self contained electrohydraulic actuators. Each actuator is capable of rendering high intensity fine tactile pressure (upto 34 kPa) and high frequency vibration (up to 700 Hz). This capability to render both pressure and vibration at this density provides a unique capability to render perceived hardness, texture, curvature, sliding contacts etc. in an AR/VR/MR environment.

In this work, we make the following contributions:

- Design and development of a novel high density (16 bubbles in 1 cm^2) self contained wearable electrohydraulic actuator array capable of rendering multimodal (fine tactile pressure and vibration) haptic feedback.
- Electrohydrualic bubble actuator capable of rendering high intensity fine tactile pressure (upto 34 kPa), large displacement (upto $2mm$) and wide vibration bandwidth (700 Hz) in a small form-factor (3 mm $\times$ 18 mm).
- Novel electrohydraulic wearable actuator architecture where the dielectric fluid is stored at the back of the fingertip to achieve high density actuation in a wearable form-factor.
- Physical characterization for the (a) quasi-static voltage-pressure behavior, and (b) vibrotactile frequency response of the actuator.
- Psychophysical characterization of the just-noticeable differences (JNDs) of the fine tactile pressure and vibrotactile frequency rendered by individual electrohydrualic bubble actuator.

II. Design of ElectroHydraulic-Haptic Interface

We developed a high intesity, high-fidelity, on-skin electrohydraulic haptic interface that is thin, light-weight, and entirely soft. It has a spatial tactile resolution of 16 bubbles per cm^2.

A. Design and Form Factor

The design of this haptic interface consists of 16 individually controlled electrohydraulic bubble actuators capable of providing multimodal haptic sensation. The actuators consists of a multi-layer design integrating mechanically stretchable silicone membrane ($20\mu m$ thickness) with a novel dielectric film (Stretchlon Bagging Film) that enables high pressure output. The dielectric films are arranged in a pouch form-factor to store a small quantity of ($5\mu l$) a dielectric oil (Envirotemp FR3, Cargill).

The design of a single actuator is divided into 3 components:

- A tactile bubble that is asymmetrically elastic
- An electrohydraulic actuator storing the dielectric fluid
- A neck that connects the bubble to the electrohydraulic actuator

The tactile bubble consists of a top stretchable layer and bottom non-stretchable layer that gives it ability to inflate asymmetrically in a preferred direction. The electrohydraulic chamber is made out by trapping a small amount of dielectric fluid in between two layer of a dielectric thermoplastic film that are covered with flexible electrodes (conductive carbon tape) on the outside (Figure 2 and 3). The electrodes are further insulated with another layer of dielectric film whose edges are further secured with polyimide tape. The neck of the actuator is embedded with elastomeric (silicone) tubes that prevent buckling of the fluidic channel when bent around the finger.

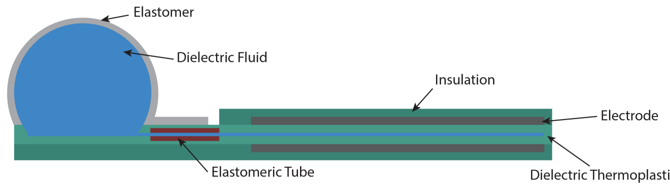

Fig. 3. Schematic of a single bubble actuator in inflated state [(when a high Voltage (4000-5000 Volts) is applied to the electrodes].

B. Operating Principle

The designed electrohydraulic bubble actuator operates between a voltage of 2-6 kV. When a high voltage (2000V) is applied to the electrohydraulic actuator, the electrodes start zipping together due to the electrostatic force between the two electrodes. As the voltage is increased gradually (to 5000 V), the actuator zips further and pushes the liquid dielectric towards the stretchable bubble through the neck (Figure 3). The bubble inflates asymmetrically out of plane with increasing voltage due to the stiffness differential between the top and bottom layer.

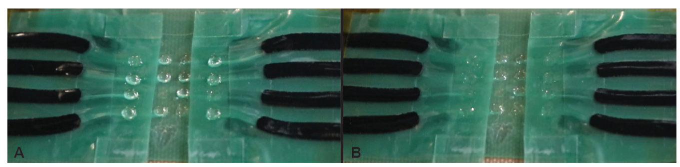

Fig. 4. The ElectroHydraulic Haptic Interface consists of 16 bubbles that can individually render fine tactile pressure as well as vibrations. Part (A) shows a pressure pattern rendered over the actuator array in comparison to (B) the non-actuated state. The black features in the image are the actuator electrodes.

C. Fabrication

This soft electrohydraulic interface consists of 16 actuators that are fabricated in two separate layers. Each layer consists of 8 actuators entirely insulated from each other. The fabrication of a layer is described in Figure 5.

At first a single sheet of thermoplastic dielectric film is pattered with 8 holes of 1.5 mm (in 2 columns with spacing of 1.5 mm) using a laser cutter. Then a thin silicone sheet (*Elastosil* $20\mu m$, lateral dimensions 18 mm x 18 mm, tensile strength 6 N/mm^2) is plasma bonded on one side of the dielectric film (centered around the hole patterns). After plasma bonding, another layer of dielectric film is overlayed on the other side of first film and 8 open chamber geometries are heat-sealed around the 8 existing hole patterns using a custom-built heat sealing machine (by modifying the head of a CNC machine). Extra care is taken to carefully align the origins of the laser cutter and the CNC so that the chamber geometries are properly aligned with the patterned holes. A small input port is left open in the chambers for filling dielectric liquid. Afterwards, thin silicone tubes are inserted through the input port to the neck of each actuator. The chambers are filled with the dielectric oil (viscosity of 34 mm^2 per second) and

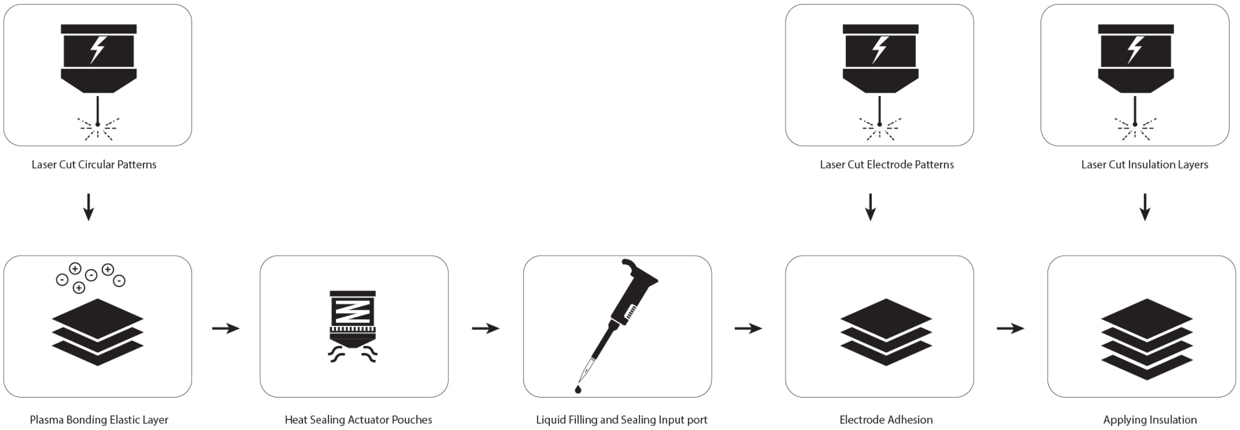

Fig. 5. Fabrication Process of the ElectroHydraulic Haptic Interface.

the input port is sealed after carefully removing air bubbles. The actuator is now ready for electrode attachment.

Flexible electrodes (3 mm x 10 mm) are laser cut out of double sided conductive carbon tape (NEM Tape, NISSHIN EM.CO) and attached on both sides of each actuator chamber (see Figure 4). A layer of dielectric film is added over the electrodes for insulation. The edges of the insulation are heat sealed and secured with polyimide tape. Actuators are now ready to be connected to a high voltage power supply and tested.

III. Technical Characterization

We characterize both the static and dynamic performance of the electrohydraulic bubble actuator. For static characterization, we establish a relationship between the input voltage and output pressure to understand the range of pressures this actuator can render. For dynamic characterization, we evaluate the displacement frequency response of the actuator. All the characterization was performed on a single bubble actuator.

A. Pressure-Voltage Characterization

To characterize the relationship between pressure, displacement, and voltage of actuation of these miniature electrohydraulic actuators, a set of quasi-static experiments are conducted. The direct measurement of pressure inside soft electrohydraulic actuator is challenging due to the very small volume of the dielectric fluid in the pouch. So instead we resort to an indirect measurement of pressure A single bubble actuator pouch (without the dielectric fluid) is inflated using a pneumatic pressure regulator (Festo VEAB-L-26-D12-Q4-A4-1R1) for a series of known pressures and the displacement of the bubble in response to the pressure is measured using a laser displacement sensor (Acuity AR100 Laser Measurement Sensor). Afterwards the same actuator pouch is filled with a dielectric liquid to construct an electrohydraulic actuator. We then make measurements of the displacement of bubble in response to the applied voltage. Figure 7A and 7C show Displacement vs Voltage and Pressure vs Voltage plots, respectively. The maximum pressure generated by our actuators is around 34 kPa, which is almost an order of magnitude higher than similar actuators reported in the literature [8], [28]. The high intensity pressure achieved by these actuators is due to the novel dielectric film (Stretchlon) in comparison to other dielectric materials reported in the literature like BoPP (biaxially-oriented polypropylene).

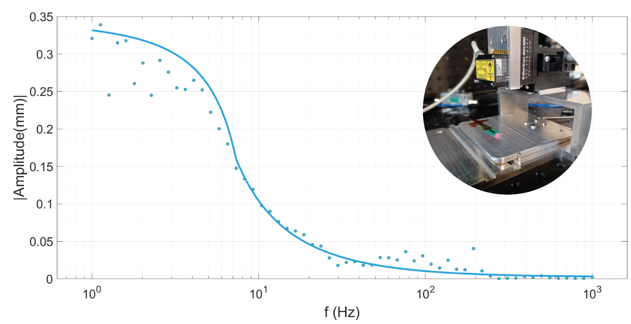

Fig. 6. Frequency response characteristics of a single ElectroHydraulic Bubble Actuator. The actuator generates perceivable vibrations up to 700 Hz. [Inset] The setup to measure the displacement and frequency response of the actuator using a laser displacement sensor.

B. Transient Characterization

Step response characterization shows that the response time of the electrohydrualic bubble actuator is 32 milliseconds. To characterize the frequency response of the bubble actuator, a set of high voltage square waves (amplitude 5 kV) at different frequencies (1 to 300 Hz divided into 50 equidistant steps in the logarithmic space) are commanded to the actuator for 50 cycles each, and resulting displacement response is recorded for each frequency. A fast-Fourier transform analysis on the commanded voltage data and measured displacement data for each frequency is then used to obtain the frequency response. The resulting displacement-frequency response plot from this analysis is shown in Figure 6.

IV. User Evaluation: Psychophysical Study

To validate the effectiveness of the haptic perception of this novel interface, we evaluated performance via a user study. The goal here is to evaluate the available perceptual space and its characteristics for the discrete haptic cues provided by

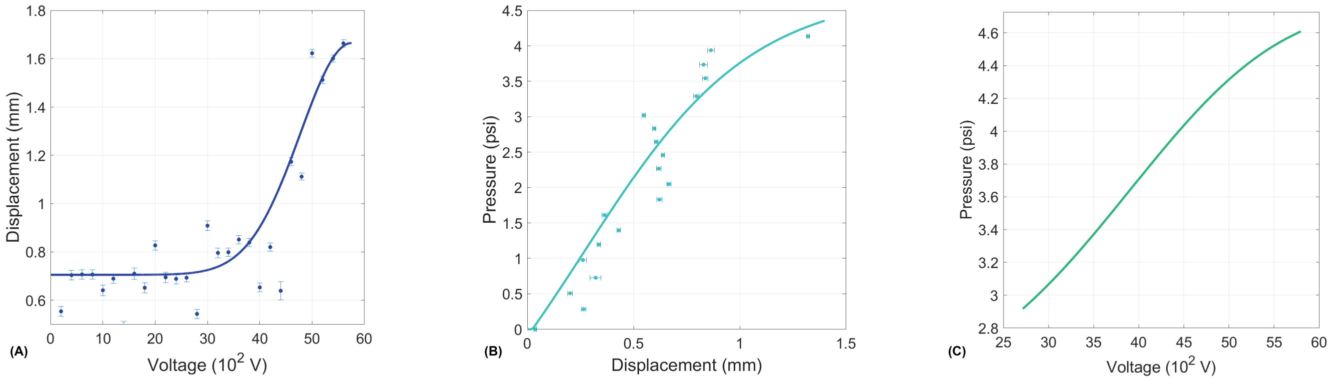

Fig. 7. Steady-state characteristics of a single ElectroHydraulic Bubble Actuator. Part (A) shows Displacement vs Voltage curve that follows a gaussian distribution. Part (B) shows Pressure vs Displacement curve while part (C) demonstrates Pressure vs Voltage curve extracted from the Displacement vs Voltage and Pressure vs Displacement data.

our interface. We aim to evaluate the frequency and intensity discrimination capabilities via the just-noticeable difference (JND) for fine tactile pressure and vibro-tactile feedback. Just like the technical characterization, all the human subject evaluation was done using a single bubble actuator. All studies were performed on the index fingertip of the dominant hand of the human subjects.

A. Intensity JND Study

We designed a study to understand the perceived intensity discrimination threshold (JND) for this actuator in response to applied voltage with a total of 9 participants (5 male, 4 female; average age 29.2 years). A set of voltages (9 values) equally spaced apart between 2500-4500 V were compared against a chosen standard of 3500 V for each participant using a 2 alternative forced choice procedure [29]. The signals were rendered sequentially on a single actuator for each pair. The comparisons were randomised and repeated 7 times. The results are shown in the Figure 8A and 9A.

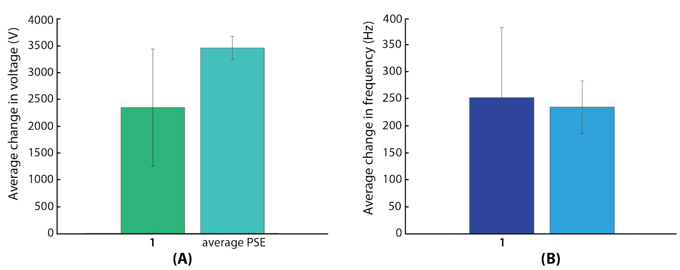

Fig. 8. Part (A) shows the average just noticeable difference (Volts) and bias or point of subjective equality (Volts) across the 9 observers. Part (B) shows the average JND and PSE (Hz) across observers.

B. Frequency JND Study

Human threshold for vibrotactile frequency at the fingertips can be as high as 1000 Hz [30]. However, beyond 300 Hz it becomes more and more difficult to reliably distinguish vibrations [30], [31]. With our setup most of the users said they could feel vibrations as high as 700 Hz but couldn't distinguish reliably beyond 300 Hz. In a second study, we explored the frequency discrimination threshold (JND) for this actuator with variations in the frequency of the applied voltage. A total of 9 participants (5 male, 4 female; average age 31.7 years) were chosen for the study. A set of frequencies (11 values equally spaced apart between 100-300 Hz) were compared against a chosen standard of 200 Hz. The comparisons were randomised and repeated 7 times for each participant. The results are shown in the Figure 8B and 9B.

C. User evaluation: implications

We explored how precisely users could discriminate a change in the pressure exerted on the fingertip via our novel soft actuator. On average users required an increase of 2300 V to robustly feel a change in the applied pressure, see Figure 9 relative to our standard of 3500 V. Participants estimate of equal pressure (PSE) across the comparison stimuli was biased such that an increase in pressure relative to the standard was required for the two signals to feel equally intense.

When we updated the frequency content of the discrete vibrations presented to the fingertip, a difference in frequency of approximately 250 Hz was needed for users to robustly determine a change in the signal. However, discrimination ability varied substantially across users, with some individuals discriminating frequency changes less than 120 Hz. The variability in discrimination abilities across observers could be attributed to a number of factors, with the difference in mechanoreceptor density at the contact location a likely candidate.

Further explorations are warranted but the current results highlight our novel display's capacity to produce discriminable changes across both vibration frequency and pressure magnitudes.

V. Discussion and Future Work

The aim of this work was to develop a high spatial-resolution, thin, lightweight, multimodal haptic interface for the fingertip. We demonstrated that soft electrohydraulic actuation is one of the most promising pathways to enable this. Though we do achieve spatial tactile resolution of 2 mm in this current prototype, we are still a bit far from the 0.95 mm resolution limit of human fingertip [32]. Clearly, we need to

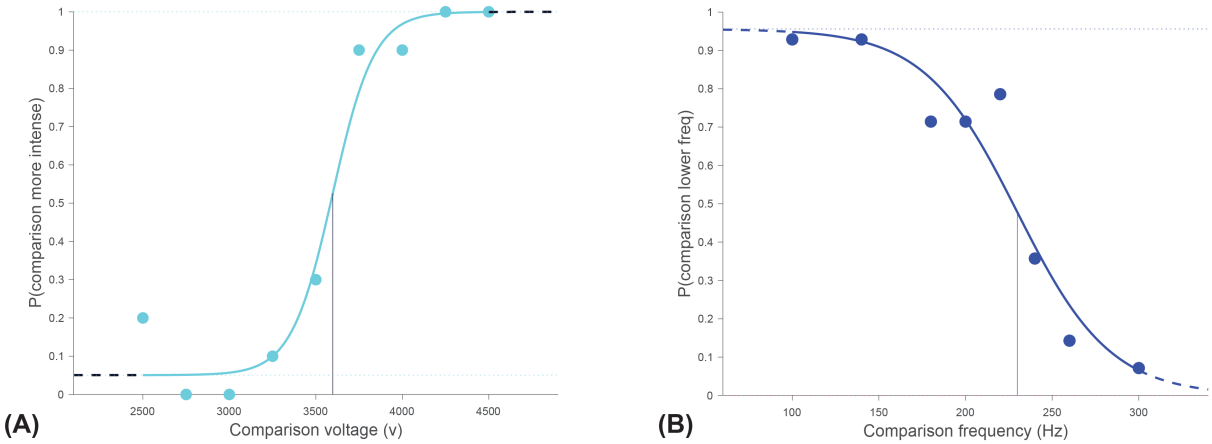

Fig. 9. Part (A) shows Intensity estimation results. Perceived intensity psychometric function for a single observer. Part (B) shows Frequency discrimination results. Example observer psychometric function fit for frequency discrimination (Hz) where observers identified which of two frequencies was lower.

almost double the density of actuators to bring a reliable sense of touch in mixed reality systems. Any such endeavour would involve serious design and fabrication challenges.

One of the challenges in perceptual characterization, especially for Frequency JND, is that it is difficult to disambiguate whether the obtained results are due to a change in frequency or a combined effect of change in amplitude in response to frequency. It is difficult to render amplitude-matched vibrations across frequencies for our actuator, especially while the actuator is in contact with the finger soft tissue, due to instrumentation challenges related to reliably capturing the actuator characteristics with human in the loop. Some evidence exists that human subjects can perceive that a vibration has higher or lower pitch than a frequency-matched comparison if its amplitude is changed [33]. This decoupling of amplitude and frequency for perceived vibrations for humans is also not well studied in the scientific community. Recent results reveal that vibrotactile pitch is computed as a product of stimulus frequency and a power function of its amplitude in humans [30]. The value of the power function exponent depends on the spectral location relative to the frequency of highest vibrotactile sensitivity.

Another design challenge is posed by the high voltage of these actuators. Though the haptic interface can be insulated in the current prototype to ensure human safety; the high-voltage control electronics becomes increasingly challenging to miniaturize as the number of actuator increases. For the current prototype, a 16 output channel, battery powered wearable power supply (in a wristband form-factor) can be explored in the future.

The operational voltage of electrohydraulic actuators can be reduced by improving the constituting dielectric materials. Our choice of dielectric film (Stretchlon) is driven by this goal. Stretchlon reduces the voltages dramatically to generate the same amount of pressure in comparison to other dielectric films like BoPP or PET (polyethylene terephthalate, commonly also known as Mylar). More research is needed to completely understand the underlying mechanism of how this voltage reduction is achieved, but we believe this may be due to Johnsen and Rahbek effect that results in additional force output due to charge accumulation on the dielectric film at the contact interface [34]. We were further able to reduce the voltage of operation significantly to 3 kV (for the same pressure and displacement) by replacing the current dielectric fluid with Novec 7500 dielectric fluid (3M). However, this fluid is extremely volatile and permeable to silicone films. In the current prototype, Novec 7500 would permeate out and evaporate completely within 24-48 hours of fabrication. This shows that the material research for soft electrohydraulic actuators is a multidimensional problem where material combinations need to be optimized not just for the dielectric performance but also for mechanical robustness and reliability of the actuator.

VI. Conclusion

We introduced a novel finger-mounted, entirely soft, electrohydraulic haptic interface capable of providing multimodal haptic feedback. The interface can render high intensity fine-tactile pressure as well as wide bandwidth vibrotactile feedback. We miniaturized the design of soft electrohydraulic actuators to conform them around the finger and build an actuator array with 16 such individually controllable bubbles to render haptic stimuli with high spatial resolution of 2 mm. To build this interface, we integrated stretchable substrates with a novel dielectric material and developed a design architecture wherein the dielectric fluid is stored at the back of the fingertip. We physically characterized the static and dynamic behavior of the device and demonstrated that the interface can render fine tactile pressure as well as perceivable vibrations up to 700 Hz. We established the perceptual performance of this actuator using psychophysical characterization through a set of user studies. We conclude that this new soft electrohydraulic device is the pathway to build a high-fidelity, low-friction wearable haptic interface with hundreds of actuators.

VII. Acknowledgement

We thank Noah Kohls for help with the experiments. We also express our gratitude to Tianshu Liu and Alexandre Poulin for early brainstorming and valuable discussions. All work was funded internally by Reality Labs Research, Meta Platforms Inc.

References

[1] R. S. Johansson and J. R. Flanagan, "Coding and use of tactile signals from the fingertips in object manipulation tasks," *Nature Reviews Neuroscience*, vol. 10, no. 5, pp. 345–359, 2009.

[2] A. Abdouni, G. Moreau, R. Vargiolu, and H. Zahouani, "Static and active tactile perception and touch anisotropy: aging and gender effect," *Scientific reports*, vol. 8, no. 1, pp. 1–11, 2018.

[3] E. B. Goldstein and L. Cacciamani, *Sensation and perception*. Cengage Learning, 2021.

[4] L. Skedung, M. Arvidsson, J. Y. Chung, C. M. Stafford, B. Berglund, and M. W. Rutland, "Feeling small: exploring the tactile perception limits," *Scientific reports*, vol. 3, no. 1, pp. 1–6, 2013.

[5] J. Scheibert, S. Leurent, A. Prevost, and G. Debrégeas, "The role of fingerprints in the coding of tactile information probed with a biomimetic sensor," *Science*, vol. 323, no. 5920, pp. 1503–1506, 2009.

[6] N. Nakazawa, R. Ikeura, and H. Inooka, "Characteristics of human fingertips in the shearing direction," *Biological cybernetics*, vol. 82, no. 3, pp. 207–214, 2000.

[7] R. V. Grigorii, J. E. Colgate, and R. Klatzky, "The spatial profile of skin indentation shapes tactile perception across stimulus frequencies," *Scientific Reports*, vol. 12, no. 1, pp. 1–11, 2022.

[8] A. K. Han, S. Ji, D. Wang, and M. R. Cutkosky, "Haptic surface display based on miniature dielectric fluid transducers," *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 4021–4027, 2020.

[9] E. Leroy, R. Hinchet, and H. Shea, "Multimode hydraulically amplified electrostatic actuators for wearable haptics," *Advanced Materials*, vol. 32, no. 36, p. 2002564, 2020.

[10] T. Han, S. Bansal, X. Shi, Y. Chen, B. Quan, F. Tian, H. Wang, and S. Subramanian, "Hapbead: On-skin microfluidic haptic interface using tunable bead," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, 2020, pp. 1–10.

[11] T. Han, F. Anderson, P. Irani, and T. Grossman, "Hydroring: Supporting mixed reality haptics using liquid flow," in *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, 2018, pp. 913–925.

[12] S.-Y. Teng, P. Li, R. Nith, J. Fonseca, and P. Lopes, "Touch&fold: a foldable haptic actuator for rendering touch in mixed reality," in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, 2021, pp. 1–14.

[13] Y. Ujitoko, T. Taniguchi, S. Sakurai, and K. Hirota, "Development of finger-mounted high-density pin-array haptic display," *IEEE Access*, vol. 8, pp. 145 107–145 114, 2020.

[14] S. Jang, L. H. Kim, K. Tanner, H. Ishii, and S. Follmer, "Haptic edge display for mobile tactile interaction," in *Proceedings of the 2016 CHI conference on human factors in computing systems*, 2016, pp. 3706–3716.

[15] C. Pacchierotti, S. Sinclair, M. Solazzi, A. Frisoli, V. Hayward, and D. Prattichizzo, "Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives," *IEEE transactions on haptics*, vol. 10, no. 4, pp. 580–600, 2017.

[16] M. Zhu, S. Biswas, S. I. Dinulescu, N. Kastor, E. W. Hawkes, and Y. Visell, "Soft, wearable robotics and haptics: Technologies, trends, and emerging applications," *Proceedings of the IEEE*, vol. 110, no. 2, pp. 246–272, 2022.

[17] W. Guo, Y. Hu, Z. Yin, and H. Wu, "On-skin stimulation devices for haptic feedback and human–machine interfaces," *Advanced Materials Technologies*, vol. 7, no. 2, p. 2100452, 2022.

[18] X. Ji, X. Liu, V. Cacucciolo, Y. Civet, A. El Haitami, S. Cantin, Y. Perriard, and H. Shea, "Untethered feel-through haptics using 18-μm thick dielectric elastomer actuators," *Advanced Functional Materials*, vol. 31, no. 39, p. 2006639, 2021.

[19] Y. Bahramzadeh and M. Shahinpoor, "A review of ionic polymeric soft actuators and sensors," *Soft Robotics*, vol. 1, no. 1, pp. 38–52, 2014.

[20] D.-Y. Lee, S. H. Jeong, A. J. Cohen, D. M. Vogt, M. Kollosche, G. Lansberry, Y. Mengüç, A. Israr, D. R. Clarke, and R. J. Wood, "A wearable textile-embedded dielectric elastomer actuator haptic display," *Soft Robotics*, 2022.

[21] M. Y. Ozsecen, M. Sivak, and C. Mavroidis, "Haptic interfaces using dielectric electroactive polymers," in *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2010*, vol. 7647. SPIE, 2010, pp. 960–966.

[22] F. Ganet, M.-Q. Le, J. Capsal, J. Duchet, A. Millon, and P.-J. Cottinet, "Haptic feedback using an all-organic electroactive polymer composite," *Sensors and Actuators B: Chemical*, vol. 220, pp. 1120–1130, 2015.

[23] E. Acome, S. K. Mitchell, T. Morrissey, M. Emmett, C. Benjamin, M. King, M. Radakovitz, and C. Keplinger, "Hydraulically amplified self-healing electrostatic actuators with muscle-like performance," *Science*, vol. 359, no. 6371, pp. 61–65, 2018.

[24] N. Kellaris, V. Gopaluni Venkata, G. M. Smith, S. K. Mitchell, and C. Keplinger, "Peano-hasel actuators: Muscle-mimetic, electrohydraulic transducers that linearly contract on activation," *Science Robotics*, vol. 3, no. 14, p. eaar3276, 2018.

[25] Purnendu, E. Acome, C. Keplinger, M. D. Gross, C. Bruns, D. Leithinger *et al.*, "Soft electrohydraulic actuators for origami inspired shape-changing interfaces," in *Conference on Human Factors in Computing Systems (CHI 2021)*. ACM, 2021.

[26] Purnendu, S. M. Novack, E. Acome, C. Keplinger, M. Alistar, M. D. Gross, C. Bruns, and D. Leithinger, "Electriflow: Soft electrohydraulic building blocks for prototyping shape-changing interfaces," in *Designing Interactive Systems Conference 2021*, 2021, pp. 1280–1290.

[27] Purnendu, S. Novack, E. Acome, M. Alistar, C. Keplinger, M. D. Gross, C. Bruns, and D. Leithinger, "Electriflow: Augmenting books with tangible animation using soft electrohydraulic actuators," in *ACM SIGGRAPH 2021 Labs*, 2021, pp. 1–2.

[28] A. Tzemanaki, G. A. Al, C. Melhuish, and S. Dogramadzi, "Design of a wearable fingertip haptic device for remote palpation: Characterisation and interface with a virtual environment," *Frontiers in Robotics and AI*, vol. 5, p. 62, 2018.

[29] G. T. Fechner, *Elemente der psychophysik*. Breitkopf u. Härtel, 1860, vol. 2.

[30] M. Prsa, D. Kilicel, A. Nourizonoz, K.-S. Lee, and D. Huber, "A common computational principle for vibrotactile pitch perception in mouse and human," *Nature communications*, vol. 12, no. 1, p. 5336, 2021.

[31] 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.

[32] R. W. Van Boven and K. O. Johnson, "The limit of tactile spatial resolution in humans: grating orientation discrimination at the lip, tongue, and finger," *Neurology*, vol. 44, no. 12, pp. 2361–2361, 1994.

[33] J. W. Morley and M. J. Rowe, "Perceived pitch of vibrotactile stimuli: effects of vibration amplitude, and implications for vibration frequency coding." *The Journal of physiology*, vol. 431, no. 1, pp. 403–416, 1990.

[34] C. D. Shultz, M. A. Peshkin, and J. E. Colgate, "Surface haptics via electroadhesion: Expanding electrovibration with johnsen and rahbek," in *2015 ieee world haptics conference (whc)*. IEEE, 2015, pp. 57–62.