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Soft Flexible Magnetic Micro-Structures for a Haptic Surface

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***Abstract*—Haptic surfaces can convey substantial tactile information, benefiting diverse applications such as robotic teleoperation, medical simulation, virtual reality (VR), and education. A critical challenge in haptic device technology is generating haptic sensations associated with mechanical compliance. Employing soft materials for adaptable interfaces that dynamically alternate between soft and hard tactile feedback further complicates this challenge. In this study, we address stiffness-controlled feedback through the design and fabrication of magnetically actuatable micro-structures using a UV-curable magnetic elastomer. These micro-structures, covered by a thin magnetic elastomer layer, form a pad that functions as an encounter-type haptic display when magnetically stimulated. User evaluations demonstrated clear differentiation in perceived softness, confirming the effectiveness of the designed haptic interface.**

***Index Terms*—haptics, micro-structures, haptic surface, haptic interfaces**

I. Introduction

Surface haptics refers to the generation of tactile feedback on fingertips through touch surfaces [1]. Within this domain, the goal of these haptic interfaces is to emulate or amplify the tactile experience associated with manipulating or perceiving a real environment through the integration of mechatronic devices and control systems that can recreate realistic haptic feedback that aligns with the physical attributes of objects encountered in real environmental interactions. These surfaces are capable of providing tactile and/or kinesthetic feedback, depending on the type of stimulation applied to the user, whether through skin contact or muscle interaction [1], [2], allowing users to freely engage with virtual environments without the need for wearable or handheld devices.

To provide haptic feedback, various actuation methods have been employed on haptic surfaces, with the three most widely used being vibrotactile [3], [4], ultrasonic [5] and electrostatics [1], [6], [7]. In addition to these techniques, other actuation methods have proven effective in delivering haptic feedback such as: electromagnetism [8], fluidic pressure [9], [10], direct neuromuscular electrical stimulation [11] and kinesthetic interaction [12]. This field still faces challenges to provide reliable haptic feedback, like expanding the haptic contact area, adapting haptic rendering to accommodate a broader range of shapes, and enabling the rendering of multiple textures simultaneously [2]. Tan et al. in [13] identify a relevant challenge in softness rendering, to accurately mimic an object's softness in a virtual environment, a soft interface is required between the haptic device and the user's fingertip.

To address this challenge, researchers have explored soft materials and micro-structures responsive to field-controlled stimulation. Magnetic actuation is especially popular in touchscreen haptics, primarily for vibrotactile feedback [14]. Some novel applications like FingerFlux [15] uses a combination of a fingertip worn permanent magnet and electromagnets to modify the perceived surface friction. Mudpad [16], uses magnetic fields to stimulate an magneto-rheological (MR) fluid and modify its viscosity. Magnetic field control has been used for contactless virtual object exploration [17]. So far, these methods have shown good results for virtual object interaction, but still involve rigid and often bulky equipment, limiting their practicality compared to small electromagnetic motors [7].

This work presents the design and fabrication of soft micro-structures for an encounter-type haptic surface and the use of a tunable electromagnetic field to actuate these structures compressing them under magnetic force. Fig. 1.a shows a CAD representation of the device, with the micro-structures mounted on the electromagnet and Fig. 1.b shows the actual micro-structures on the mounting plate. Fig. 1.c shows the interaction of the micro-structures with a user's fingertip while being pressed to evaluate a virtual object's softness.

Following a brief review of fields related to this study, we describe the design and fabrication of these micro-structures using a custom-made magnetic elastomer patterned with a high-resolution digital light processing (DLP) 3D printer. Next, we describe a user study we developed for device validation, and discuss the results obtained from the experimental

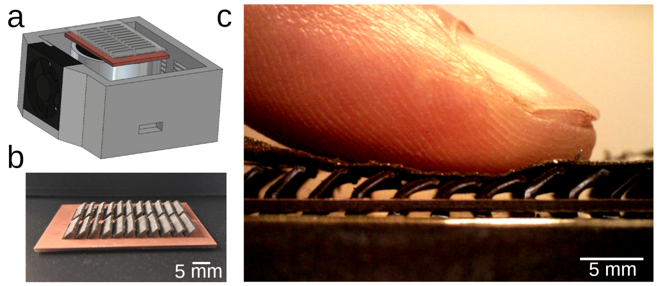

Fig. 1. Micro-structured Haptic Surface. a: CAD representation of the device uncovered with all components mounted in their place. b: 3D printed micro-structures placed on the mounting plate. c: User's finger pressing the surface showing how these collapse under the user's finger to provide haptic feedback.

testing validating the analytical model and the user study. Finally, we present our conclusions regarding the functionality validation of the developed haptic surface. By implementing a controllable electromagnetic field, the device demonstrates the ability to actively adjust surface stiffness, providing haptic feedback to users.

II. Related Work

Here we briefly review three research topics related to the design and function of our device: (i) tactile haptic surfaces, (ii) variable stiffness control, and (iii) electromagnetically actuated soft materials.

A. Tactile Haptic Surfaces

Surface haptics provide tactile feedback to users by modifying the interaction forces between finger contact and a stationary surface during touch. The actuation methods can be classified according to the finger's direction of motion [1]:

- *Normal to the surface*: These kinds of interfaces use mostly mechanical actuators to generate a normal vibration or pulses [1], [14], [18]. Some of the actuation methods used for these purposes are piezoelectric, electroactive polymers, and electromagnetism, or multimodal devices like the HapTable described in [19]. Although the specific sensation of softness has been mostly addressed through kinesthetic feedback through finger worn devices [12], there are studies that compliant surfaces can provide a user with tactile feedback related to stiffness or softness of a virtual object, like the origami prismatic joint described in [20], or particle jamming actuators from [21].
- *Tangential to the surface*: In this case, vibro-tactile stimulation is the most widely used technique to provide haptic cues to the user [22] by modulating the vibration frequency of a surface by the implementation of vibrational motors, ultrasonic waves, electrostatics and voice coil actuators [1]; there are also actuators designed to recreate textures or provide physical cues to the user as they slide their finger across the surface, some of the actuation technologies studied are: microfluidic actuation [23], [24], pneumatics [25], shape memory alloys [25] and electroactive polymers [26]. Guo et al. in [27] introduced the use of a magnetically actuated elastomer array to recreate textures with millimeter-level resolution.

B. Variable Stiffness Control

Inspired by biological organisms, such as some echinoderms that can control their inner dermis stiffness at will [28] or some species of horsetail that can vary their stiffness due to environmental factors [29], multiple materials and techniques have been studied to achieve controllable stiffness. Shape memory polymers (SMP) have been especially popular, as they can vary their stiffness through chemical, thermal, or electrical stimulation [30]–[33].

Metamaterials have also been designed to provide adjustable stiffness [34]–[37] for actuators in different applications. Recently, Ghoddousi et al. developed a Fibonacci spiral-shaped metamaterial that increases its stiffness under compression [38], Lin et al. combined a bistable metamaterial with SMPs, showing tunable stiffness due to thermal stimulation [39]. In addition, Yang et al. demonstrated that a haptic thimble can stimulate touching sensation of a wide range of materials ranging from soft gel to metallic surfaces [37].

Other techniques for stiffness tuning include pneumatics [40], hydraulics [41], [42], tensioning cables [43], [44], and particle jamming [45], like the device developed by Stanley et al. where the jamming of coffee ground can render different levels of stiffness and a wide range of surface geometries [21].

C. Electromagnetically Actuated Soft Materials

Electromagnetic fields have emerged as a compelling actuation method for soft robotics, offering potential across diverse applications. By embedding soft substrates with magnetic particles and aligning their magnetic domains via strong magnetic fields, magneto-responsive materials are created. These materials enable soft robots to perform complex motions with notable accuracy, adapting their pose, position, or shape when exposed to external magnetic stimulation [46], [47]. The combination of the mechanical properties of the substrate with the versatility of magnetic actuation has further enabled the development of shape-shifting materials [48]. For example, Jeon et al. designed an array of magnetic micropillars that can modify the surface pose, twisting or bending it [49].

Magnetic stimulation has been used with MR and ferrofluids to achieve tunable stiffness in soft haptic interfaces, leveraging their reversible changes in mechanical properties under magnetic fields to enable real-time control of compliance for effective softness rendering [16], [50]–[53]. For example, Ishizuka et al. present an array of MR fluid cells whose stiffness can be modulated through applied magnetic fields, enabling users to perceive varying degrees of softness and hardness across the display surface [54].

In summary, while existing approaches to haptic surfaces, stiffness modulation, and electromagnetically actuated soft materials have demonstrated effective tactile feedback or tunable mechanical properties, many rely on complex mechanisms, or fluidic systems that constrain their practicality and integration. The interface proposed in this work distinguishes itself by combining a magneto-responsive micro-structured surface with a compact and passive architecture that enables fast, repeatable, and perceivable stiffness modulation. Moreover, its modular design allows for scaling across different surface areas and form factors. This combination of simplicity, responsiveness, and scalability positions it as a promising alternative for immersive applications such as virtual interaction.

III. Stiffness-tuning Haptic Interface

This device is a soft compliant surface with micro-structures that can be actuated using electromagnetic fields to modify their height to recreate different sensations of stiffness for the surface. This surface measures 25 x 35 mm enough for an average human fingertip to interact with, providing haptic feedback to the user.

A. Fabrication

The micro-structures for the haptic surface were manufactured using a high resolution DLP 3D printer (Asiga, Pico2HD@27) with a UV curable elastomeric resin embedded with 20% neodymium-iron-boron (NdFeB) particles (5 μm, MQF™, Magnequench) for the magnetic response. The elastomeric resin consisting of epoxy aliphatic acrylate (EAA, Ebecryl 113, Allnex USA), aliphatic urethane diacrylate in a 1:1 ratio by weight. 4% photo-initiator (Genocure BAPO, Rahn USA Corp. and Genocure CPK, Rahn USA Corp. in a 2:1 ratio by weight) with respect to the total weight of the elastomeric resin [55], [56]. The photoinitiator was dissolved in the elastomeric resin by stirring in a 90°C water bath. Fig. 2.a shows a graphical representation of this process.

3D printing was performed at 40°C and each layer, of a thickness of 50 μm, was irradiated for 10 s. After printing, the micro-structures were cleaned in a two-stage isopropyl alcohol (IPA) bath, 3 minutes per stage, followed by magnetization using an electromagnet with a vibrating-sample magnetometer (VSM, LakeShore 7400) at 1 T for 3 minutes. The resin was then UV-cured for 6 minutes. As shown in Fig. 2.b.

The micro-structures were then covered with a layer of styrene-isoprene-styrene (SIS, Sigma-Aldrich 432393-500G) block co-polymer elastomer which was prepared by dissolving it in Toluene in a 4.2:1 ratio by weight, and placed on a hot plate at 90°C until it melted. Micro sized ferromagnetic neodymium-iron-boron (NdFeB) powder (Magnequench MQP-15-7-20065-085) was embedded in the uncured elastomer and mixed using a planetary mixer (THINKY ARE-250) for 3 minutes at 2000 RPM. Fig. 2.c shows this process.

A 20 μm layer of the elastomer was prepared on a glass slide using a thin film applicator and left to cure for 3 hours inside the fume hood at room temperature (20°C). Once cured, this layer was magnetized following the same procedure described for the micro-structures. As shown in Fig. 2.d. This film was then mounted, covering the micro-structures, and these were placed atop the electromagnet.

The device was encapsulated in a 3D printed case that held the electromagnet and haptic surface in place for adequate actuation of the micro-structures, as seen in Fig. 1.a.

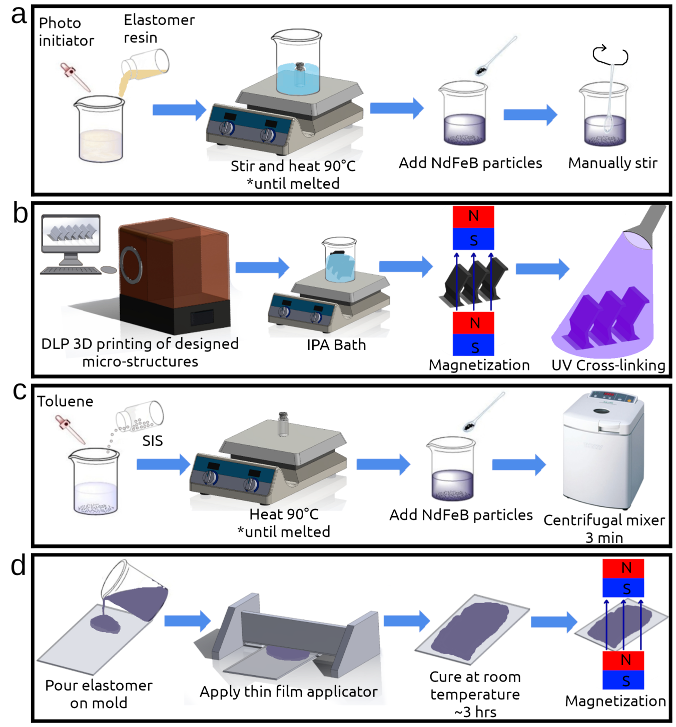

Fig. 2. Magnetic haptic surface fabrication process stages: a: Photo-curable magnetic resin fabrication. b: Fabrication of the micro-structures. c: Magnetic elastomer fabrication. d: Thin magnetic elastomeric film fabrication.

B. Mechanical Characterization

To characterize the mechanical properties of the composite used for this device, we conducted mechanical testing using an Instron tensile tester (model 5969U5571), using a 50 N static load cell (model 2530-50N). To evaluate the effect of embedded particle fillers on the stiffness of the material, we performed an ASTM-D412 tensile test. For this purpose, dog-bone samples were 3D printed, but scaled down to 1/6 of the ASTM standard size to fit within the DLP 3D printer building platform [57]. From the test results, we obtained a Young's modulus for this composite of 1.77 MPa, a plot with the resulting strain/stress curve can be seen in Fig. 3.a.

Using the measured Young's modulus, we applied an Euler-Bernoulli beam model to predict how a single 3D-printed micro-structure would deform under compression, estimating its height with equation (1).

$$h = h_0 - \frac{F \cos\alpha L^3}{3EI}\,. \tag{1}$$

Here, h_0 is the initial height of the micro-structure, F is the applied force, L is the length of the bending part of the structure, E corresponds to the Young's modulus of the material, and I to the second moment of inertia of the structure. Fig. 3.b-d show a graphical representation of the model and its parameters. The parameter α corresponds to the angle of the structure, which will decrease as the structure is compressed,

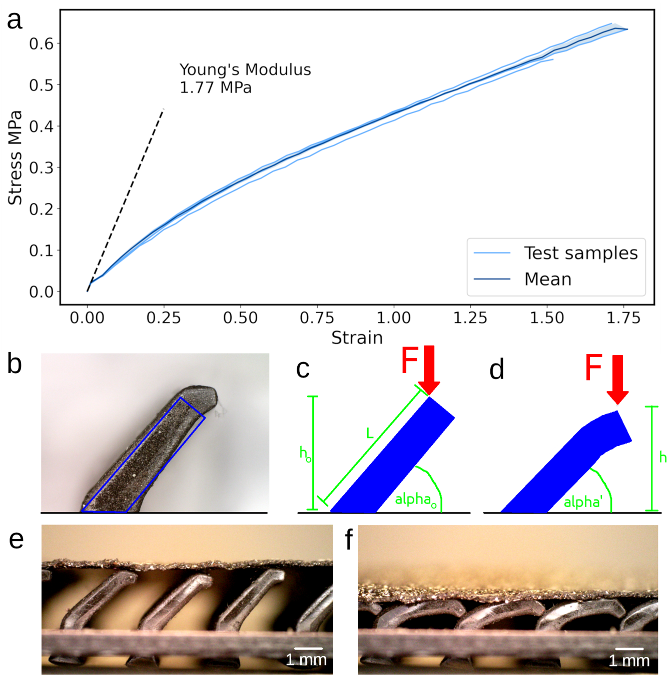

Fig. 3. Micro-structures analytical model a: Experimental Strain/Stress curve. b: Graphical superposition of the beam geometry used for the model. c: Free body diagram at the micro-structure's initial position. d: Free body diagram at the micro-structure under compressive force. e: Side view of the micro-structures in an unactuated condition. f: Side view of the micro-structures under a magnetic field of 110 mT, corresponding to full magnetic compression.

as shown in Fig. 3.d-f:

$$\alpha = \arcsin\left(\frac{h}{l}\right). \tag{2}$$

It is important to note that this model does not account for the elastic deformation of the material itself, which may lead to deviations between the predicted and actual behavior under compression, particularly at higher force levels.

Subsequently, experimental measurements were conducted to evaluate the deformation of a 10×30 mm array of micro-structures under compressive loading conditions, across a range of magnetic field intensities from 0 to 110 mT. Compression was applied from the array's surface until the micro-structures were observed to be fully collapsed. This meant a total compression of 1.2 mm in the unactuated state and 0.7 mm in a fully actuated condition. As the magnetic field increased, the initial parameters h_0 and α_0 decreased, resulting in greater effective stiffness. As shown in Fig. 4.a, the structures exhibited increased stiffness and reduced compressibility with greater stimulation of the magnetic field. Fig. 4.b shows a comparison of the compressive force needed for 0.7 mm compression under different levels of magnetic field stimulation, indicating an effective stiffness modulation.

As seen in Fig. 4.c, the analytical model shows strong agreement with the experimental data throughout the compression range (initial part of the curve), suggesting that the micro-structures exhibit a soft mechanical response, compressing significantly under light pressure. To quantify the model's accuracy, the root mean square error (RMSE) between predicted and measured forces was calculated as 0.011 N, corresponding to only 8% of the total compressive force range. This low error confirms that the model reliably predicts the mechanical behavior of the micro-structured surface. However, once the compression exceeds a critical displacement of approximately 1.2 mm, the micro-structures fully collapse, leading to a marked increase in effective stiffness. Further compression beyond this point was not considered in the model, as the motion of the micro-structures could no longer be described as beam bending but rather as the deformation of a flexible solid under compression.

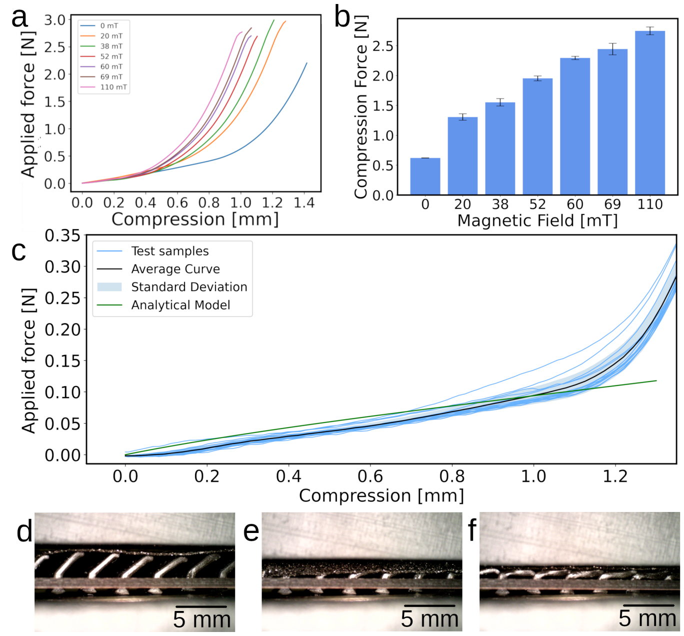

Fig. 4. Mechanical Characterization: a: Compression test results under different magnetic fields. b: Compression force evaluation for a 0.7 mm compression under different magnetic actuation. c: Analytical model compared with results from unactuated compression tests. d: Side view of unactuated micro-structures. e: Side view of actuated micro-structures. f: Side view of micro-structures under full compression.

C. Controller

The magnetic field used to actuate the haptic surface was generated by an electromagnet (Adafruit, model WF-P40/20) powered through an adjustable DC-DC Buck converter (Digikey, DFR0379), both controlled via an Arduino UNO. By digitally regulating the current supplied to the electromagnet, the magnetic field could be tuned from 0 mT to 110 mT, enabling precise control over the compression of the device's micro-structures. A schematic representation of the system is shown in Fig. 5.

D. Dynamic Response

The dynamic response of the haptic interface was characterized by measuring the time required for the microstructures to transition between actuation states under magnetic stimulation.

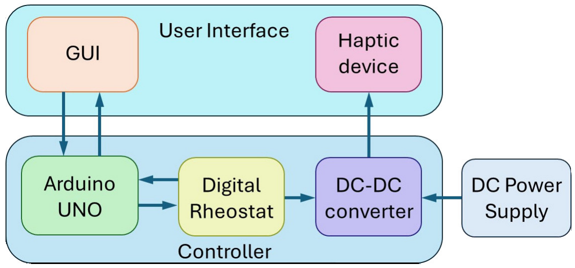

Fig. 5. Block diagram of the control system used to generate a variable magnetic field, enabling tunable stiffness on the soft haptic surface.

Full compression from the unactuated state (110 mT) was achieved in an average of 60 ms, while full recovery required 180 ms. When actuated to an intermediate stiffness level (60 mT), the structures reached the corresponding deformation in 28 ms, with a return time of 95 ms. These response times indicate that the device meets typical temporal requirements for interactive haptic feedback, particularly in virtual environments [14], although the recovery delay may influence perception during rapid or repeated interactions.

IV. Haptic Feedback Evaluation

To evaluate our device's ability to dynamically vary their softness, we conducted a user study with 15 participants using a two-alternative forced-choice paradigm with the method of constant stimuli [58]. All participants gave their informed consent, and the protocol (STUDY2024_00000278) was approved by Carnegie Mellon University Institutional Review Board under Expedited Review per 45CFR 46.110.

The users had to compare the perceived softness of these surfaces by exerting pressure on the pad with their dominant hand's index finger, according to the exploratory procedure described in [59].

A. Experimental Setup

A total of 10 users (7 men and 3 women) participated in this study. The ages of the participants ranged from 22 to 38 years, and 2 subjects were left-handed. No participants reported known sensorimotor abnormalities.

Referring to Fig. 6.a, the device used for this study consisted of two different 35 x 25 mm pads mounted on the top part of a 3D printed case that held the electromagnets and the pads on top. Participants were asked to use the index finger of their dominant hand to interact with the device. The device's surface was covered so that the user could not see the pads and only using his index finger could perform the stiffness comparison. Fig. 6.b shows a user's hand interacting with the device.

For users to interact with the device we used a Graphical User Interface (GUI) where they were asked if one surface felt softer than the reference one. Fig. 6.c shows the GUI that was used during the study.

B. Experimental Procedure

The haptic device was placed on a table and all participants were required to sit in front of it, where they could interact

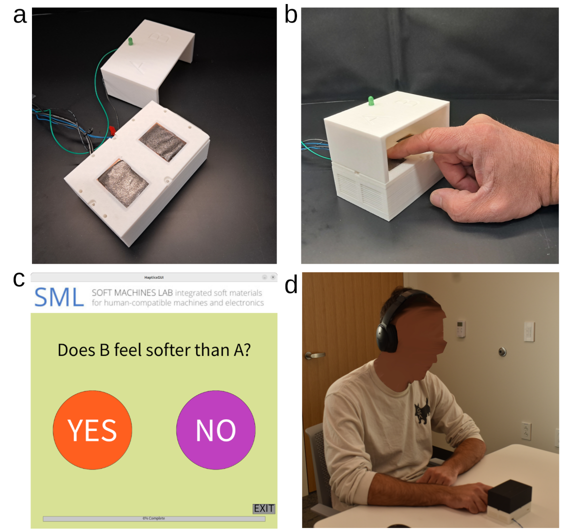

Fig. 6. User Study. a: Device used for the user study with two soft haptic pads for user interaction. b: Example of user interaction, index finger pressing one of the pads to evaluate its softness. c: Graphical User Interface showing the question asked to the participants and the two options for them to answer. d: User interacting with the device during testing session.

with the device using their dominant hand and at the same time, see the GUI to follow the study instructions. The participants wore noise canceling headphones to suppress any electrical noise coming from the electromagnets to avoid sound cues. Each participant completed a practice round before the main experiment during which they experienced each pad being stimulated once. Fig. 6.d shows one of the subjects.

C. Methods

A two-alternative forced-choice experiment was conducted, following the method of constant stimuli [58]. Subjects were asked to press their index finger against one pad at a time and compare their stiffness. Using the GUI they would have to choose which of these surfaces felt softer. For each test round, one of the surfaces presented a reference magnetic field value of 60 mT, while the other displayed a comparison value, which corresponded to 0, 30, 85 and 110 mT.

Each comparison value was presented seven times in a random order, totaling 28 trials per participant. Users could freely push both pads with their index finger and select their response via the GUI, with no time limit. In case the decision seemed too difficult, participants were required to make their best guess. All responses were recorded at the end of the test.

D. Results

The study yielded an average Weber fraction of 0.27, indicating moderate perceptual sensitivity to changes in stiffness in the range tested. The point of subjective equality (PSE) averaged 54.22 mT, reflecting a slight perceptual bias toward underestimating the reference stiffness. The mean just-noticeable difference (JND), measured at 32.56 mT, defines the smallest detectable change in magnetic field intensity perceived by users as a difference in softness. Fig. 7 shows the

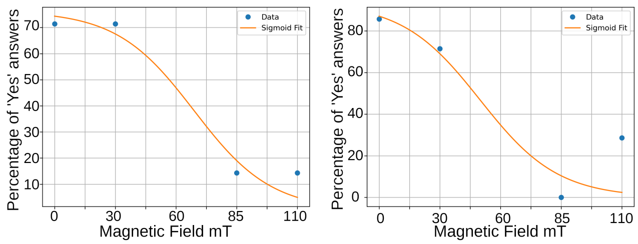

Fig. 7. User Study. Two example s-curves obtained from the user study showing the percentage of yes answers to the softness comparison question.

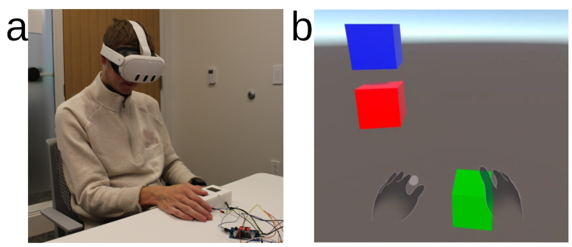

Fig. 8. Virtual Reality Testing. a: User wearing the headset interacting with the device. b: Virtual environment used for the demo.

resulting s-curves from two test subjects. These psychophysical parameters validate that the proposed haptic interface can reliably convey variable stiffness sensations, supporting its utility for applications that require nuanced tactile feedback. The results demonstrate the system's capability to modulate softness within perceptible thresholds, which is critical for effective haptic rendering in virtual environments.

E. Use case demonstration

To demonstrate the practical functionality of the proposed haptic surface, we performed a virtual interaction scenario using a Meta Quest 3 headset. In this demonstration, a user engaged with a virtual environment by tapping on simulated objects while physically interacting with our device, which served as a tangible prop, as shown in Fig. 8. The device actively modulated its surface stiffness in real time to reflect different virtual material properties, providing users with distinct tactile cues corresponding to soft or stiff objects. This interaction created a compelling illusion of material variation through localized changes in compliance.

The demonstration underscores the potential of the interface in immersive applications that benefit from real-time tactile feedback. These may include virtual training, physical rehabilitation, and interactive media experiences in which material perception enhances user engagement. Although this was not a formal user study, it effectively validated the device's ability to deliver meaningful and dynamic haptic feedback.

V. Results & Discussion

To evaluate the stiffness modulation under a tunable magnetic field, compression tests were conducted on the device. The experimental results were then compared with theoretical predictions derived from the proposed analytical model. The comparison demonstrated strong agreement within the operational range prior to a full collapse of the micro-structures, indicating that the model provides reliable and accurate estimations for use in practical haptic interface applications.

The user study further validated the system's ability to convey haptic feedback. Participants were able to distinguish variations in surface stiffness modulated by different magnetic field intensities, confirming the perceptibility of the actuation.

The device's rapid response time meets latency requirements for real-time virtual environments [14], enabling its integration into interactive systems such as VR and assistive technologies. Unlike particle jamming methods, which rely on enclosed chambers and slow fluid dynamics, this interface provides sub-100 ms actuation without internal moving parts, offering a faster and more scalable alternative for dynamic stiffness modulation. Nonetheless, limitations such as material hysteresis, slower recovery times, and integration challenges must still be addressed for deployment in real-world applications.

The proposed interface benefits from a design that eliminates the need for enclosed chambers or fluidic networks, common in particle jamming systems. Its compatibility with soft lithography and additive manufacturing techniques facilitates scalable production. The absence of internal moving parts further enhances reliability and integration flexibility, making it suitable for various applications.

These findings highlight the feasibility of using magnetic actuation in micro-structured surfaces to deliver dynamic haptic feedback. Compared to conventional vibrotactile or electrostatic methods, this approach offers a mechanically tunable and scalable alternative capable of conveying stiffness-based cues without relying on surface vibration.

VI. Conclusion

A novel tactile haptic surface was designed and fabricated for studying the user's perception of stiffness in virtual surfaces. The device can provide tactile feedback on the user's fingertips that can be perceived by the user as different levels of stiffness. A psychophysical experiment was conducted that demonstrated the functionality of the device.

This work introduced a UV-curable magnetic elastomeric composite that could be patterned with a 3D printer to function as a soft and compliant haptic surface. The use of DLP-based 3D printing allowed for the fabrication of micro-structures that could be further improved to enhance the device's performance and expand its range of possible applications.

This is a novel application that, thanks to the use of soft and flexible magnetic micro-structures, can be applied for haptic surfaces for rendering different levels of softness by varying the micro-structure's geometry through variable magnetic fields.

Lastly, an Euler-Bernoulli cantilever beam model was used to model the micro-structure bending motion under compressive pressure with a reasonable degree of accuracy. Such a model has the potential to provide design insights that could be used to further vary the design of the device and examine alternative micro-structures for improved tactile feedback.

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