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Multi-mode soft haptic thimble for haptic augmented reality based application of texture overlaying☆

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ABSTRACT

This paper presents a novel thimble-shape haptic display for multi-mode tactile feedback at fingertips. The device has two special characteristics. Multi-mode feedback, i.e., static pressure, high-frequency vibration, and impact force, can be generated via a single actuator mechanism of a pneumatic chamber controlled by high-speed valves. Additionally, the actuator's softness makes this device a "feel-through" tactile display where the user simultaneously feels responses from a real object and synthetic feedback. This makes the device a fit for haptic augmented reality-based display where real and virtual touch feedback is merged into single feedback that haptically "augments" the real world.

A layered combination of flexible and non-flexible silicone membrane surrounds the air- cavity for desired efficiency, and systematic valve control algorithms are developed for rich haptic effects. The experiments confirmed that the system generated a static force up to 7 N, acceleration magnitude up to 1.4 G, and frequency up to 250 Hz. The device exhibits two realistic tactile signals, i.e., virtual textures and button clicks, based on real signals and a physical surface that are augmented with two haptic signals.The user studies revealed that the participants found the virtually overlaid textures and buttons to be perceptually similar to their real counterparts.

1. Introduction

Future generation multi-sensory human–computer interfaces are envisioned to simulate the sensation of an object touch within a virtual environment. A tactile display empowers the user with haptics - the sense of touch –within the VR/AR-based environment for immersive experiences [1].

Haptic augmented reality (AR) merges real and virtual haptic feedback to enhance a real touch sensation [2]. Mixing real and virtual touch feedback has several benefits. Compared to environments with pure synthetic feedback (i.e. virtual reality), haptic AR provides ease of creating high fidelity haptic contents. The system only deals with a small portion of the feedback that needs to be modified or emphasized, and the rest of the feedback is taken from real environments, which saves computational cost, minimizes hardware while keeping high realism. Another benefit of mixing is that, although real objects are involved in the haptic interaction, the beneficial flexibility of synthetic feedback is still preserved.

One of the main enabling technologies of the concept of haptic AR is a "feel-through" display. Interfaces for haptic AR should have a "feel-through" capability in order to allow a user to simultaneously feel responses from a real object and those made by a computer, analogous to see-through displays for visual AR [3]. In order to fully utilize the potential of haptic AR, an ideal feel-through displays should cover the entire spectrum of tactile transparency; from completely blocking the real feedback (as interfaces for VR) to full tactile transparency (as a haptic probe). This degree of tactile transparency should be even controllable in real-time. Two different approaches are possible: direct feel-through and indirect feel-through [3].The former lets signal from real environments is to be directly transmitted to the user while

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additionally adding synthetic signals to the feedback, which is similar to optical see-through in visual AR. The latter, similar to video see-through, senses real signals, mixes them with synthetic ones, and renders the mix using a conventional haptic device for VR. While the latter is technically easier, the former can be considered as ideal feel-through since it maximizes the advantage of haptic AR in the aspect of utilizing the high fidelity of real feedback, which is not limited by the performance of the tactile displays.

In practice, realizing this direct feel-through tactile display is not an easy task. Different from vision, haptic sensation is evoked usually by mechanical stimulation, e.g., force, pressure, and so on, and thus haptic actuators should be mechanically coupled with human body parts in order to properly stimulate mechanoreceptors in the human skin and joints [4]. This mechanical coupling should be often located on a body part at which the sensation is to be generated, i.e., a point on the skin where either actual or virtual contact occurs. This is fine for pure VR where the whole stimulation is made by the actuators. However, this is one of the major hurdles that hinder the direct feel-through for haptic AR. In most cases, the actuators are rigid and located in-between the user's skin and the real environment, and thus they partially or completely block the delivery of physical signals between the real objects and the skin.

In order to tackle this hurdle, this paper introduces a haptic thimble: a soft and thin pneumatic actuator for a finger-worn feel-through haptic display as shown in Fig. 1. The actuator is made of thin layers of silicone, allowing the user to directly feel the kinesthetic part of stimuli from real objects while interacting with it. In addition, the actuator is incorporated with a small pneumatic bladder in the layers operated by pneumatic valves, which allows adding various tactile effects upon the real kinesthetic feedback. The "tactile transparency" can be also partially controlled in a programmable manner. If the context needs direct delivery of a real object's geometry, the air bladder becomes thin by sucking the air through it to allow the user to feel it. The thimble can also completely block the real kinesthetic information through the damping of the blown bladder between the finger and the object.

Another advantage of the configuration is that due to our systematic valve control and bladder layer design, multiple distinctive effects are possible via a single actuator. In addition to static pressure feedback up to 7 N, fast valve control generates high-frequency vibrations with a bandwidth of up to 250 Hz and sudden impact feedback on the finger. Besides, the pneumatic actuation inherently allows us to keep all the rigid assembly for the actuation, e.g., pneumatic valves, pumps, and control circuits, away from the finger, and thus a minimal amount of assembly can be left at the location of contact. Eventually, during the interaction with real objects, a user wearing the soft thimble can perceive the shape and macro geometry information coming from the real object while simultaneously perceiving overlaid synthetic haptic effects, including pressure, vibration, and impact, well-registered to user's interaction and context. One of the promising scenarios of the interface is that if combined with a visual AR headset, any static and non-responsive physical contents, e.g., a picture printed on a piece of paper, texts in a book, or prints on a cloth, can be turned into haptic feedback- enabled dynamic contents.

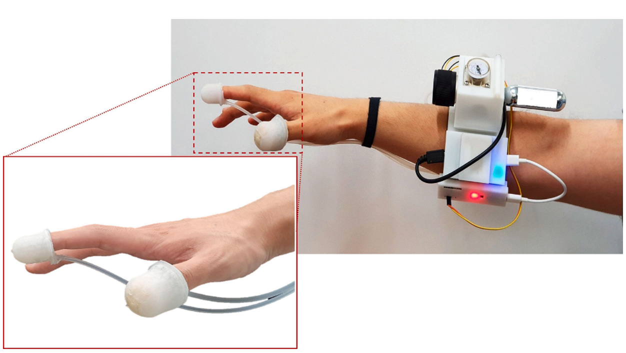

Fig. 1. Thimble shaped soft tactile display.

The paper is structured as follows. After reviewing the related work, three main sections follow. Section 3 presents the fabrication of the end-effector and control. Section 4 is characterizing its performance and describes the system setup. Section 5 presents the rendering algorithm of the whole interface and demonstrates the potential by presenting two haptic augmentation application examples: haptic texture overlaying and button clicking overlaying. Section 6 evaluates the approach in terms of perceptual performance. Finally, we conclude the paper in Section 7 with the future directions.

2. Related work

This section first reviews the current status of haptic AR research and then moves to the previous attempts on fingertip haptic feedback devices.

2.1. Haptic augmented reality

The advances in the core technologies for visual augmented reality, e.g., vision-based head and hand tracking and optical see-through displays, inherently increases the attention on the need for haptic feedback in the mixed reality environment. Initial efforts were on the haptic rendering of virtual objects embedded in an AR environment (e.g., [5–8], refer to [3] for thorough review).

While unique issues were there, e.g., visuo-haptic registration and stability of haptic feedback, researchers quickly found that haptic rendering of embedded virtual objects fundamentally shares the same principle with the techniques used for pure VR [2]. They found that another emerging category for haptics in AR is the mix of the haptic signal itself and that merging real haptic signal with virtual haptic signal significantly broadens the potential of haptic-enabled AR. The focus is now moving to this *augmentation of haptic sensation*, and several fundamental researchers and application examples have been around in the haptics research community (see [3] for an in-depth review of them).

In the contemporary paradigm, for augmented haptic feedback, the user experiences haptic feedback with the help of a proxy object. The haptic experience can either be in the form of a direct or indirect feel-through, as explained earlier. The indirect feel-through interfaces modulate real signals, and the user experiences purely synthesized signals. In some cases where the feel-through is implemented indirectly, they rely on a stylus [9], haptic glove [10], a grounded force feedback device [11], or other such intermediate links for interaction. In a manner, the sense of augmentation is fulfilled, however, no real and direct contact is allowed by maintaining a rigid link in the middle.

Direct feel-through is achieved by providing the user with real signals, from the interaction object, in addition to the virtual signals. The real signals are either compensated or meaningfully enhanced by the virtual signals. This is the approach that has been followed in the proposed system as well. Direct feel- through can be used to augment either one or both kinesthetic and tactile cues in a mixed reality environment. In the case of kinesthetic feel-through interfaces, the force feedback is augmented to enhance or diminish the haptic effect. For example, augmenting force feedback from virtual sliders and buttons on a real desk [12], modifying the stiffness of real objects [13], or a digital milling device for sculpting [14]. Direct kinesthetic feel-through also finds its application in the field of medicine, i.e., palpation of virtual tumors in real tissue mockups [15], or using an enhanced surgical probe to magnify the haptic effect from interaction with cartilage-like material [16].

Direct feel-through can also be utilized in augmenting the tactile response of real objects. Researchers have been able to successfully modify the sensation of real textures by using various devices for direct feel-through. For instance, creating a squeeze film effect from ultrasonic vibrations to alter the texture of real surfaces [17], augmenting interaction signals from real surfaces in real-time using a wrist-worn actuator [18], a finger-worn actuator [19], or a stylus [20]. Furthermore, Park et al. [21] augmented a real button with virtual vibrations to produce button click sensations.

Although all the prior work on direct feel-through has successfully delivered the benefits of the concept, one of the major shortcomings of them is the lack of generality. Most of the work focuses only on the augmentation of a specific kind of tactile signal and interaction (e.g., high-frequency acceleration signals from stroking or tapping).

2.2. Finger wearable interface

One of the most sensitive and essential human body parts for exploring an object is the fingertips. The significant role of the fingertip when interacting with and exploring objects has been attracting many haptic researchers, and several haptic fingerworn interfaces are available. The previous examples of the interface can be roughly classified into two types: tactile finger interface attached to the kinesthetic device and standalone wearable.

The former tried to provide tactile-kinesthetic combined feedback by replacing the end-effector of the conventional force-reflecting interface with a finger-worn tactile display. In haptic devices, the finger-worn device can be used to explore several kinds of tactile feedback. Vibrotactile feedback can be provided by shaping the end-effector as a thimble [22], a pin-array [23], or a ring [24]. In other researches, the end-effector is used as a contact feedback interface, i.e., for touch interaction [25], geometry exploration [26,27], virtual object manipulation [28,29]. The tactile interface can also be used to provide feedback for slip and slide interaction [30]. Tactile actuators attached to a grounded haptic interface provide both precise cutaneous and kinesthetic feedback but compromises the portability, size, and wearability and affect immersiveness.

The second type of interface, i.e., standalone finger interfaces, focuses more on the wearability and usability aspect of the device. These devices can consist of single or multiple actuators for providing myriad haptic feedback. Various haptic modalities such as force [31–33], vibrotactile [33–35], interaction [36,37], thermal [35], pressure [36], shear force [38–41], geometry [35] feedback are provided using a wide range of actuators. i.e., motors [34,36,39,40,31,41,42], pneumatic bladders [32], voice coil actuators [35], LRA [33], peltier cells [35], electrostatic brakes [43], Dielectric Elastomer Actuator (DEA) [44], and recently developed pneumatic actuated structure for softness stimuli [45], activated by internal an electrostatic force [46], with self-sensing capability using close loop control [47] etc.

Most of the work uses single actuation technology, being capable of producing only one type of haptic feedback. Some tried to provide multiple kinds of tactile sensations for the richness of the feedback by assembling multiple actuators [48], but they suffered from low usability and applicability due to the bulkiness and complexity of the device. We previously confirmed that the combination of fast-operated pneumatic actuation with a flexible end-effector enables multi-mode haptic feedback, static pressure, vibrations, and impact force, with very simple structural complexity [49,50]. In the present work, thanks to the flexible nature of the actuator, we propose to use a similar actuation paradigm for a direct feel-through interface whereby users can perceive the geometry and macro texture of real objects, while the virtual texture, pressure, and impact feedback can be provided using the pneumatic bladder.

3. Soft thimble actuator

Fig. 2 illustrates the overall design of our soft-thimble actuator. The design consists of a layered structure of a flexible membrane, cavity, and non-stretchable membrane. These layers are stacked with a confined edge, such that when they are activated using pneumatic actuation, the flexible layer is on the inside and stimulates the finger pad directly (see

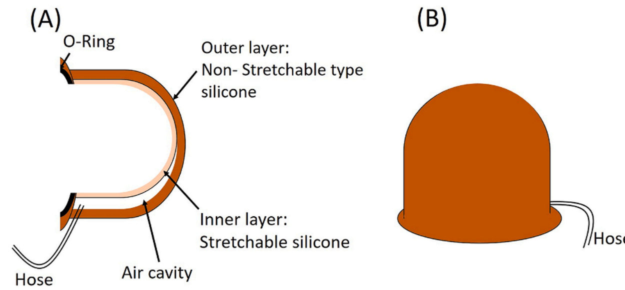

Fig. 2. Illustration of the conceptual design of the soft thimble actuator: (A) cross-section view (B) Top-view of thimble.

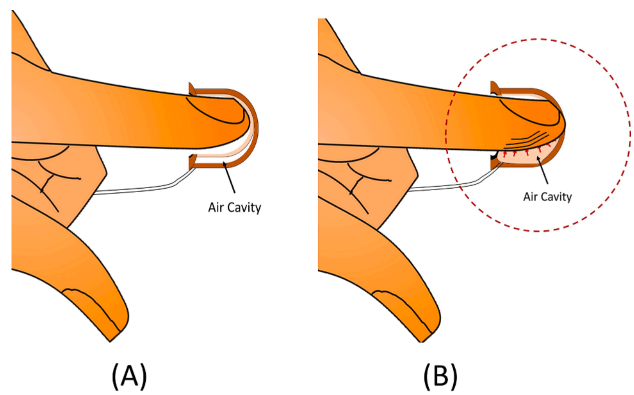

Fig. 3. Inside-air effect in a single silicone cell. (A) Normal condition (B) Blown effect.

Fig. 3). When air pressure blows into the cavity, the flexible layer elongates and stimulates the finger by pushing forces, while the non-stretchable layer obstructs the inflation outside to maintain the shape and size. The air cavity covers the 18 mm area of the fingertip in order to make strong and effective feedback and o-ring supports tight confinement at the closing end of soft thimble which allows finger movements easily (see Section 3.1).

The following subsections describe how the actuator is fabricated and controlled.

3.1. Fabrication

The material we used for the fabrication of the soft layers is a platinum-catalyzed silicone EcoFlex 00–50 (smooth-on Inc. USA). It is lightweight, appropriately soft for wearing, and has high tensile strength enough for large blowing up even when thin (100% modulus at 12 Psi), making it an appropriate choice for our prototype [51].

The fabrication process for the soft actuator is similar to our previous work [49]. It has three main steps: i) analysis of the design to construct the 3D-printed mold, ii) casting a layered structure of the stretchable membrane, air-cavity, and non-stretchable membrane, and iii) plugging the flexible hose and sealing carefully.

The first step is to analyze the desired shape and size of a physical actuator and mold. The computer-aided design (CAD) dimensions are shown in (a) Step 1 of Fig. 4. The dimensions used in this study can be adjusted to make thimble actuators of different sizes.

The second step is casting a bell-shaped layered architecture, which starts with fabricating the non-flexible outer layer. It begins with a piece of thin and soft fabric (Boryung; Atomild premium, Korea) inserted into the mold 3D-part 1. The mix of a silicone composition of Part A and Part B of the Ecoflex 00-50 in an equal amount is poured into mold 3D-part 1 followed by a tight covering of 3D-part 2 of the mold (step 2 (i) and (ii) in Fig. 4). The implantation of the piece of fabric in the silicone makes

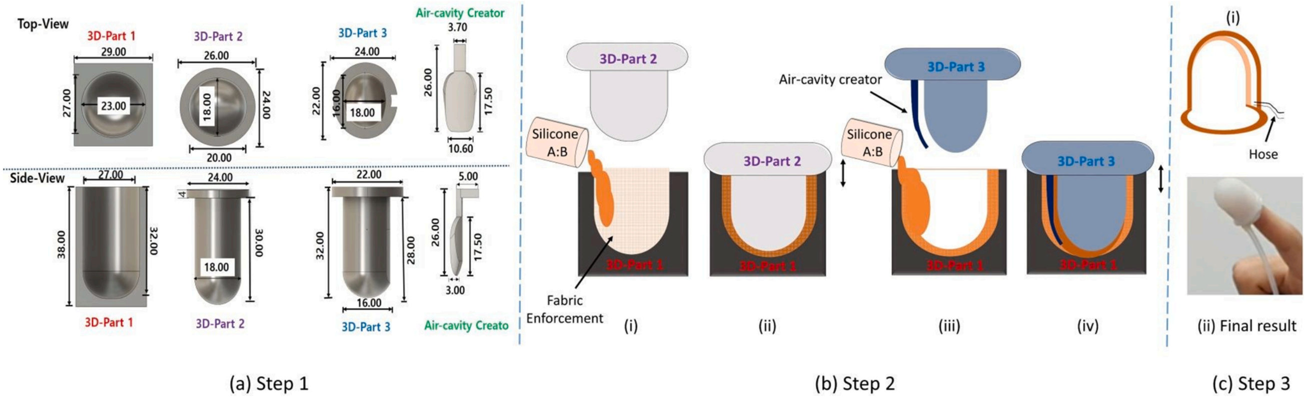

Fig. 4. Fabrication process of the soft thimble actuator: (a) Step 1: analysis of the design of mold, (b) Step 2: silicone casting process for stretchable and non–stretchable membranes, (c) Step 3: gluing a hose and the final fabrication result.

the layer non-stretchable while preserving its stiffness. It is kept on rest for 4–5 hours at room temperature for silicone curation. Note that while wrapping, the edges of the fabric should overlap and be glued with each other to avoid undesired stretch due to the gap of the fabric.

The next step is to take away 3D-Part 2 of the covering. For the stretchable membrane, pour fresh Ecoflex 00–50 silicone mix into the mold 3D-Part 1 while fabric embedded thimble-shape membrane inside ((b) Step 2 (iii) in the Fig. 4).

A careful silicone degassing with a vacuum degassing machine should be done to avoid air bubbles in the flexible membrane. Finally, tightly close the mold 3D-Part 1 using an air cavity creator attached with the mold 3D-Part 3 (see Fig. 4 (b) Step 2 (iv)). This mold set is kept on rest for another 4–5 hours at room temperature to be cured. The third step is to carefully remove the silicone structure from the mold 3D-Part 3, clean excess silicone around it, and plug a flexible hose in the inlet of the air cavity. A silicone rubber adhesive (Sil-Poxy, smooth-on, Inc.) is used to seal it properly. As an example, the fabrication result is shown in Fig. 4 final result. The total weight of the actuator was about 8 g. From our experiment, the durability of the actuator is high enough to be used frequently for six months. We used only one actuator for the rendering test and the user experiments in this paper, and no tear-down or shape change has been observed.

3.2. Pneumatic control

We used pneumatic actuation to generate haptic effects through the thimble actuator. The basic mechanism is taken from our previous publication with modifications [49]. The electropneumatic control unit is shown in Fig. 5. Varying the air pressure inside the air-cavity creates various haptic feedback. The air pressure under the cavity can be controlled using one solenoid positive pressure valve (SC0526GC, Skoocom Technology Co., Ltd.), which is connected to a compressed air supply (12 g CO_2 cartridge) using a dialed air regulator. The base

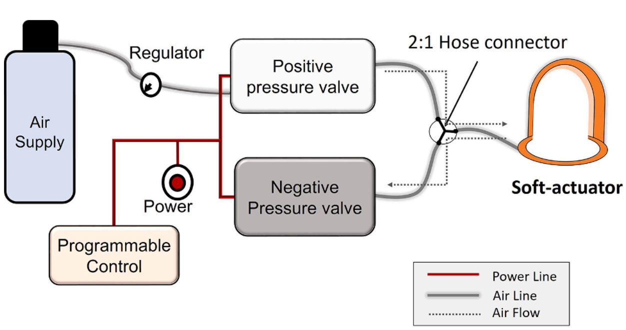

Fig. 5. Electro-pneumatic control of the soft thimble actuator.

pressure from the tank can be set manually controlling the dial at the regulator. In this work, we used the base pressure of 4 Psi or 7 Psi, which are found as optimal in our purpose. The outlet of the positive pressure valve is connected to one end of a 2:1 hose connector using a flexible hose of length 370 mm. Another end of the connector is plugged at the inlet of a negative pressure valve to release the pressure. The remaining end of the hose connector is attached to the thimble actuator. This complete set-up is operated by a 6 V DC power supply.

In our set-up, we used a 32-bit microcontroller with a custom-made MOSFET transistors board. However, any advanced programmable digital microcontroller can be used to achieve fast controlling. Two digital outputs send the ON-OFF command to control the valves. Opening the positive valve for a specific duration induces air pressure inside the chamber, while a negative valve is used to release the air pressure. Systematic and synchronous control of the valves creates various haptic feedback: vibrotactile, static pressure, and impact. Refer to [49,50] for more details of the rendering algorithms for the effects.

4. Characterization of actuator

In this section, various mechanical aspects of the actuator are characterized, based on which the systematic approach to control the system to render various haptic effects is discussed. To this end, a series of experiments are performed, and results are evaluated. In all measurements, an actuator made of Ecoflex 00–50 was tested under the base pressure 4 Psi and 7 Psi.

4.1. Acceleration response in vibration

Synchronously opening and closing both positive and negative valves create vibration stimuli. The proportional opening duration of both the valves creates a cycle (duty cycle). We set a duty of 50% for the synchronous opening and closing of both valves alternately. To do this, positive and negative valves are set at the same duration. For the characterization, we examined the rendering result of the vibration by measuring the acceleration of the actuator under various input parameters. Eleven different frequencies, i.e., 1, 2, 5, 8, 12, 24, 50, 63, 83, 125, and 250 Hz, were rendered during the measurement to evaluate the vibration characteristics of the setup using 50% duty cycle. The magnitude change was measured while rendering different frequencies.

Fig. 6 shows the vibration measuring setup. The measurements were performed using an accelerometer (ADXL335; Analog Devices, Inc.), which was fixed inside the thimble, such that the z-axis was facing the air cavity. The accelerometer was glued using a thin layer of silicone adhesive on the inflating surface of the flexible layer. Data Acquisition Board (NI-DAQ 6009; National-Instrument Inc., USA) and Analog Input Recorder (Matlab; Mathwork Inc.) were used to collect the acceleration

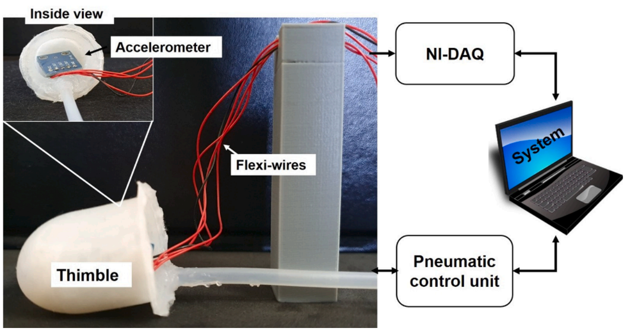

Fig. 6. Vibration measurement experimental setup.

data. The data were collected for 5-seconds at a 1 kHz sampling rate. Scotch tape was used to hold the actuator in one place during rendering. The average value of three measured accelerations was considered for each data point to minimize the effect of sensing noise.

The acceleration measured under various frequencies at 50% duty cycle is shown in Fig. 7. As predicted, a high magnitude was observed at the higher base pressure, i.e., 7 Psi with lower frequencies. This is because the longer the valve remains open, the more air gets in and inflates the cavity more, hence the high magnitude of acceleration.

While the maximum acceleration performance is achieved at 10 Hz, very powerful vibration can be generated until 70 Hz (almost 1 G at 70 Hz). In addition, the amplitude of the vibration is perceptually high enough until 250 Hz. The acceleration magnitude at 250 Hz is 0.28 G and 0.05 G at 7 and 4 Psi, respectively, which is still higher than the human perception threshold at 250 Hz (ranges from 0.08 to 0.1 ms^{-2} [52,53]). In conclusion, the frequency bandwidth of the actuator is quite wide enough to cover a perceptually useful frequency range for vibrotactile feedback. In particular, different from conventional linear resonance actuators, piezo actuators, and recently developed pneumatic actuated soft structure [54] that usually have very narrow usable bandwidth around resonance frequency, our actuator has a very flat and wide frequency response across the bandwidth, which is an exceptional behavior.

4.2. Static pressure response

The opening duration of positive and negative pressure valves determines the amount of pressure inside. Opening the positive valve only for a specific duration and holding air inside the chamber creates a static pressure effect. In this experiment, we evaluate the relationship of the opening duration of a positive valve against the force exerted on the fingerpad.

Fig. 8 shows the experimental setup for static pressure measurement. We have used one FlexiForce^{TM} medium version force sensor (A201-

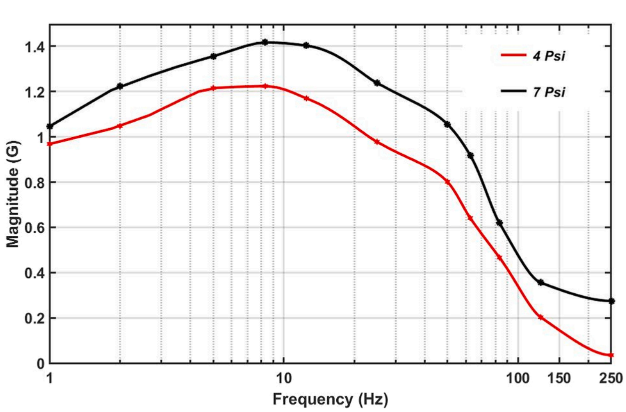

Fig. 7. Measured acceleration amplitude against frequency (Hz).

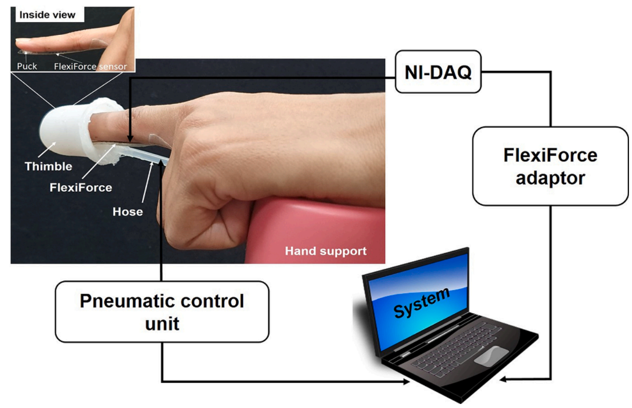

Fig. 8. Pressure measurement experimental setup.

0–25 lb; Tekscan, Inc., USA.), which was attached to a subject's index fingerpad a using double-sided scotch tape. A rigid puck was glued to the sensitive area of the force sensor for stable measurements [55].

In particular, different from conventional linear resonance actuators, and piezo actuators, our actuator has a very flat and wide frequency response across the bandwidth, which is an exceptional behavior.

The force sensing resolution of the FlexiForce was 0.1 N using a 10-bits AC-DC converter, which is sufficient accuracy for static pressure measurements and to find the trend in force. Force measurements were performed at 3 ms intervals in the range of 2–500 ms. The average of three measurements was considered for each data point to minimize sensing error.

Fig. 9 depicts the force magnitude changes versus the opening duration of a positive valve. As expected, opening duration has a direct relationship with force change, i.e., the longer the opening duration, the more significant the force magnitude. Also, the higher the base pressure the highest the inner pressure under the cavity.

Overall, within 150 ms, the actuator can generate up to 7 N force at the finger when base pressure is set to 7 Psi, while at a base pressure of 4 Psi it exhibits 2.3 N of force, which is sufficient pressure for many haptic related applications [56].

4.3. Impact response

The impact feedback is the consequence of creating static pressure and quickly releasing using a vacuum valve. The experiment in Section 4.2 measures the static air pressure while opening a positive valve. Using the same setup and procedure, we measured the pressure exerted on a finger while releasing air pressure using the negative valve. To do so, initially, we created static air pressure with a 500 ms opening of the positive valve then released the pressure at 3 ms of step intervals using a

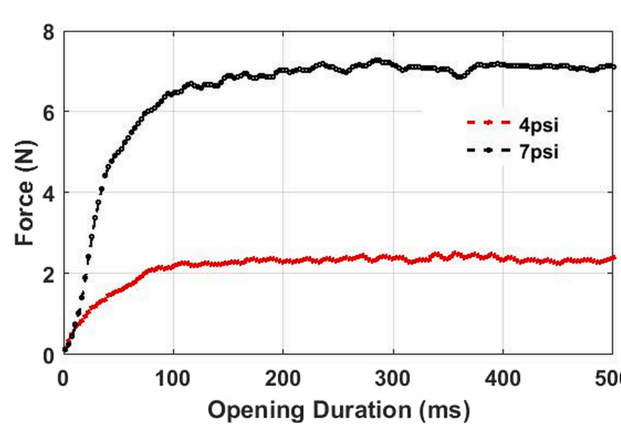

Fig. 9. Opening duration of positive valve vs rendered pressure.

negative valve. Simultaneously, the forces on the finger were measured using the force sensor.

Fig. 10 illustrated the opening duration of the negative pressure valve (ms) vs force. Note that the whole created air pressure releases within the 60–80 ms of duration. Our previous study supports a similar actuation mechanism that has a minimum delay of 5 ms in the response, which is perceptually negligible [49,50]. Altogether, it indicates that creating static air pressure and quickly releasing it creates the perception of impact feedback. An example of impact feedback for 175 ms is given in Fig. 11.

5. Haptic augmentation

Realistic rendering of haptic texture and button click are two of the more challenging topics in the field of haptics, and they are sometimes used as a benchmark for assessing a haptic system. To evaluate the capability of our system in these two scenarios, we designed an application of overlaying virtual textures and virtual buttons on a physical surface. In particular, these two scenarios can be considered representative scenarios for haptic augmentation. For instance, the idea for the first scenario was that kinesthetic properties (i.e., stiffness, geometry) of the real surface are naturally supplied by the environment, while the haptic texture properties of the surface can be concealed and replaced by other synthetic textures. Similarly, the second scenario keeps static properties of the real surface while overlaying dynamic tactile effects, i.e., button click. A typical wooden deck was used as a support surface for haptic rendering.

The following sections describe the implementation details to realize this interaction while the evaluation of the fidelity of this interaction through user-involved realism experiments is discussed in Section 6.

5.1. Tracking system

A real-time tracking environment is required to facilitate the above functionalities in the system. The system consists of a pre-registered platform (upon which the virtual content is rendered), an external optical tracking system including markers at the user's fingertip, and a film-type flexible force sensor. We opted for a high-level optical (infrared) position tracking system (OptiTrack V120: Trio NaturalPoint, Inc.) due to its 6-DoF, robustness, high precision, and real-time support [57]. The tracker is used to register the positions of the platform and track the position and velocity of the finger. The force sensor is used to register contact versus no contact force while an actuator simultaneously displays the haptic feedback. The table top positions are calibrated using OptiTrack reflective markers and Motive software to enable the overlaying effect at the specific location. For the latter, a spherical (3 mm diameter) retroreflective marker was glued on the upper side of the thimble actuator over the nail-tip but the outside of the thimble. We

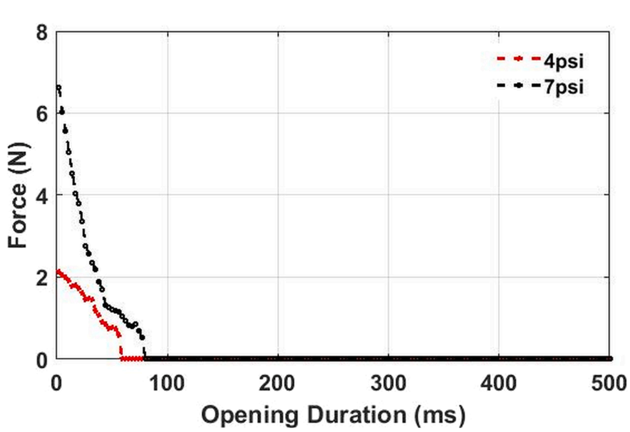

Fig. 10. Opening duration of negative valve vs rendered pressure.

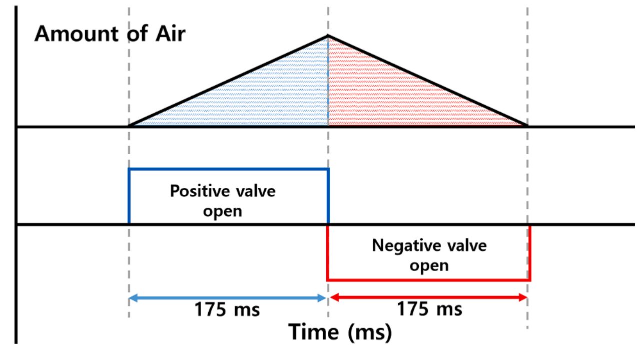

Fig. 11. An example of impact profile for 175 ms of valve opening duration.

used the MotiveAPI software to enable real-time tracking [58].

We optionally employed a thin flexible force sensor (FlexiForce A201; Tekscan, Inc., USA.) attached underneath the thimble (below the finger pad) in order to more precisely detect the contact between the finger (wrapped by the thimble) and the surface. Note that this is optional for the experimental purpose only. The sensor is flexible but not stretchable, so it may partially block the kinesthetic feedback (e.g., microgeometry) from the real surface, being against the goal of the work. In a real application, other non-obstructive options can be applied, e.g., embedding sensors underneath the surface. When a user initiates the contact, the algorithm starts rendering the augmented content through a thimble haptic display. Overall interaction system setup is illustrated in Fig. 12.

5.2. Rendering

In the previous section, the actuation characterizations of the thimble were detailed and discussed. These characteristics are used to render various haptic content in a virtual or augmented haptic environment. In this section, the thimble is used to render different haptic textures and button click responses. The details of rendering these contents are provided in the following subsections.

5.2.1. Texture rendering

In general, tool-based haptic texture rendering is achieved by providing velocity-dependent high-frequency vibrations when stroking the surface. Real surfaces have complex vibration characteristics when stroking depending on the micro-geometry of the surface [59], and

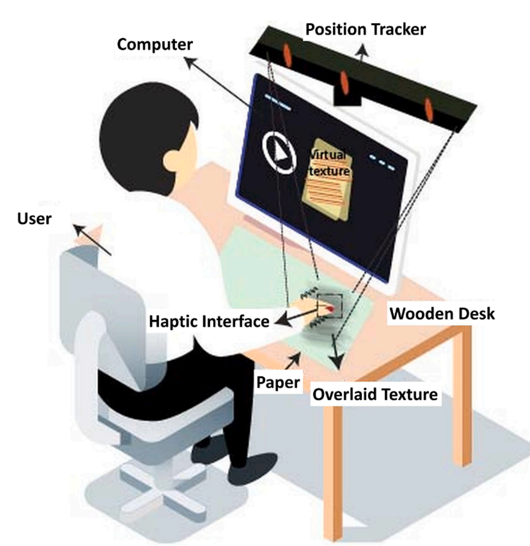

Fig. 12. Application: Overlay virtual textures.

different surfaces have different frequency and amplitude characteristics [60]. In our rendering algorithm, we simplified this characteristic; the difference is implemented by a grid system, similar to one introduced in [4]. Every target virtual surface has dense virtual grids on them. When a user's finger moves across one of the grids, the system creates a pneumatic impulse. Every virtual surface has a unique density of the grids and corresponding amplitude of the impulse, resulting in different frequency and amplitude characteristics for each surface.

During rendering, the movement of the finger is tracked using the external optical tracker. The moment when the user touches the real surface is detected either by purely position-based or the force sensor-based. For the former, the system declares the contact if the z (vertical)-position of the finger is below a threshold. For the latter, the system detects the touch by checking if the force sensor reading is higher than a pre-defined threshold. Then, the system identifies the overlaying texture model associated with the position of the touch. When the user strokes the surface, the system detects the moment when the fingertip crosses one of the grids and triggers the impulse with associated amplitude. When the user moves finger fast, multiple grids crossing may happen in one haptic loop. To deal with this, the number of grids crossing is calculated using the current and previous positions of the finger, and the system sends multiple impulses to commend in a single tick. The microprocessor sends impulse commends to the valve via a separate CPU thread in order to minimize the feedback delay. The virtual surfaces mimicked by our system are detailed in Section 6.

5.2.2. Button click rendering

A sudden change of pressure at a certain displacement point is one of the perceptually significant points during button pressing. This rapid change is usually due to the buckling of the internal structure of the button. Our goal in this scenario is to mimic this short burst of pressure, which is realized by the impulse feedback rendering.

As mentioned earlier, our approach can provide an impulse response with sufficiently high force by injecting air into the air cavity and then by quickly releasing it. By adjusting the duration of opening, various buttons with different buckling characteristics can be generated. Similar to the texture rendering, the system first detects the collision of the finger by watching the force sensor or position of the finger. Then, if the position is registered to the virtual button, a button click event is triggered. The thimble then provides an impulse/impact response to the user in accordance with the type of the button. The button feedback is generated by a single impulse response, shown in Fig. 9. The details of the virtual button responses are provided in Section 6.

6. User studies

A user experiment was designed to check the validity and usability of the proposed system. At the same time, these experiments showcased the variety of feedback that can be generated using the proposed device. The evaluation was divided into three sub-parts. The first part assesses haptic texture rendering. The textures were virtually overlaid on top of a real texture. The experiment consisted of a similarity rating exercise where the users gauged the perceptual similarity between real textured surfaces with virtually overlaid textures. The second part compares virtual pushbuttons against a real pushbutton. The third part consists of a user experience study where the users rated the usability and realism of the system while interacting with the virtually overlaid textures and the pushbuttons. The experiments are explained in detail in the following subsections.

6.1. Realism experiment - Textures

A set of real textures were compared against their corresponding virtually overlaid textures.

6.1.1. Participants and stimuli

For the device validity and usability study, we used the optimum baseline for the number of participants as suggested [61], a total of N = 11 participants (ages 25–33, 9 Male and 2 females) took part in the experiment. Seven of them had previous experience with haptic devices, while others had no prior exprience. The participants were given KRW 10,000 for their participation (approximately 30 min for experiments).

We limited our exploration to the index finger among all fingers because of two reasons; its high sensitivity for perceiving differences in spatial textures [62] and to reduce the setup complexity at the preliminary stage.

The stimuli for this experiment were a set of four real textures, as shown in Fig. 13 (excluding the last button), and corresponding four virtual textures. These textures were selected to exhibit the full range of the haptic capabilities of the device.

During the experiment, the real textures were perceived by bare-hand interaction while virtual textures were explored by the soft thimble, using the same finger by removing device multiple times to avoid a discrepancy in the perceptual sensitivity between the two hands. The rendering parameter of each of the virtual textures was separately determined through extensive manual tuning in order to make them best represent the corresponding real texture. For instance, the number of grids (2 grids per 1 cm) of the four virtual textures were 111, 250, 11, 142, respectively from the left to right in the Fig. 13. All textures were rendered at 4 Psi base pressure. In the augmented reality environment, four different regions on the desk are assigned to the four textures.

6.1.2. Procedure and analysis

Before the experiment, participants were allowed to get used to the experimental setup and explore all the real and overlaid textures for approximately 2 min. During the experiment, participants wore headphones playing white noise and a blindflod to restrict visual and auditory cues. They freely interacted with the textures using their index finger and freehand motion. For this work we limited our exploration for one finger, i.e. index finger due to the most sensitive fingers for perceiving differences in spatial textures for both sine and square virtual gratings.

The experiment was a similarity rating exercise with modulus. One real texture was provided at a time, and the participants were asked to compare it to all the virtually overlaid textures and rate them. They were asked to rate the similarity on a scale of zero to ten, zero being completely dissimilar (having no similarity whatsoever), and ten being exactly the same (having no discernible difference). Each participant carried out two trials. The order of stimuli was randomized across trials and participants using the Latin squares method to avoid bias. The participants were allowed to take breaks between the two trials. On average, one trial took around 15 min.

The data from the experiment were in the form of similarity ratings. Since the scale was fixed prior to the experiment, there was no need to normalize the readings. The data from all the users across both trials were averaged.

6.1.3. Results and discussion

Fig. 14 shows the rating results. It is observed that all the associated real and virtually overlaid textures received the highest similarity ratings. It shows that the participants were able to successfully distinguish the virtually overlaid textures and associate them with their real

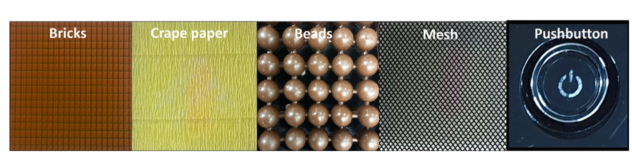

Fig. 13. Real textures and push-button used for virtually overlaid textures user study.

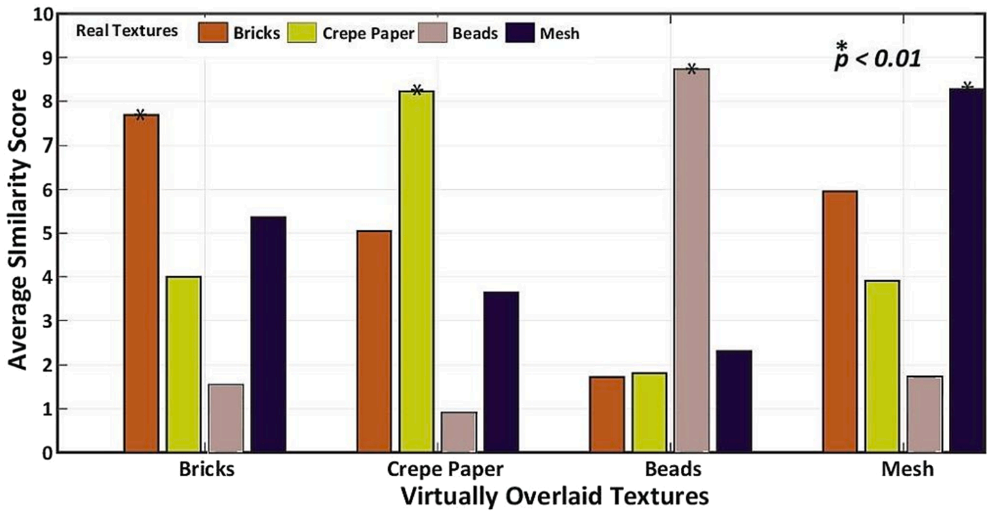

Fig. 14. Similarity ratings for the real and virtually overlaid textures. Each bar against a virtually overlaid texture represents a real texture.

counterparts. In order to find the mean value of the associated texture that is statistically significantly different from others, one way ANOVA analysis was carried out. All the associated textures showed a p-value of less than 0.01 and F = 21.8.

The similarity ratings for the texture of the bricks show a high similarity to the mesh and vice versa. Since the bricks and mesh were similar in texture and overall perception, the participants found it hard to distinguish them clearly. The beads' texture turned out to be the most distinguishable as it was markedly different from all the other textures.

Overall, for all textures, the absolute similarity between the correspondences is an average 7.7 out of 10 score on the (subjective) similarity scale. This indicates that in addition to the discriminability, the absolute realism of the feedback was also satisfactory (higher than 77 %). This is in particular a very promising result, considering that a direct real-virtual comparison is conducted, which is much more challenging than rating realism without real reference. Also, many simplifications are applied to our rendering algorithm due to the limited controllability (e.g., not possible to generate arbitrary waveform), compared to the state-of-the-art algorithms in haptic texture rendering (e.g., [63–65]). This clearly shows the advantage of haptic augmentation setup: the synergy effect of combining the real hard surface feedback with virtual tactile feedback on realism. In conventional texture rendering for pure VR, support for stroking is either absent or supplied by imperfect force reflecting haptic device [4], which significantly decreases the overall fidelity of the feedback. Besides during the experiment, we observed that the same texture rendering in the air (without real surface support) with the same actuator, exhibits compelling fidelity and immersion to the user.

6.2. Realism experiment - Buttons

The second experiment was designed to test the button click rendering capability of the device. For this purpose, a couple of virtual pushbuttons were rendered and compared against a real pushbutton.

6.2.1. Participants and stimuli

The same participants took part in this experiment. The stimuli in this experiment were two virtually overlaid pushbuttons and one real pushbutton. Both virtual pushbuttons were rendered at a pressure of 4 Psi, the point of difference being the amount of air pushed in at that pressure. One button was rendered by opening the valve for 75 ms, while for the other valve was opened for 175 ms. The button with a higher amount of air naturally created higher pressure.

6.2.2. Procedure

The participants wore a blindfold and noise-canceling headphones playing white noise during the experiment. The virtual buttons were rendered on a plain piece of paper at two different locations. The participants interacted with the virtual buttons while wearing the thimble device. The real button was provided to the participants, and they were asked to rate its similarity with the two virtual buttons on a scale of zero to ten. Initially, the participants were allowed to get familiar with the device and the virtual buttons.

6.2.3. Results analysis and discussion

The similarity data were averaged across all the participants, and the results are shown in Fig. 15. ANOVA analysis showed that the two groups of data had statistically significantly different means with $p < 0.01$, and F = 72.05.

It can be seen that participants found the higher pressure button to be more similar to the real push button. The fact that the high-pressure button received a similarity score of above 8 means that it exhibited a higher value of realism. Some of the participants commented that the feedback was very realistic, and it felt easily identifiable. One of the participants commented that “Buttons are recognized easily and button feeling seems accurate.”

6.3. User experience

The main focus of the third experiment was to test the qualitative characteristics of the system. It is important to find out if the users are comfortable using the proposed device and if it causes any unwanted hindrances during the interaction. Similarly, to find out if any other

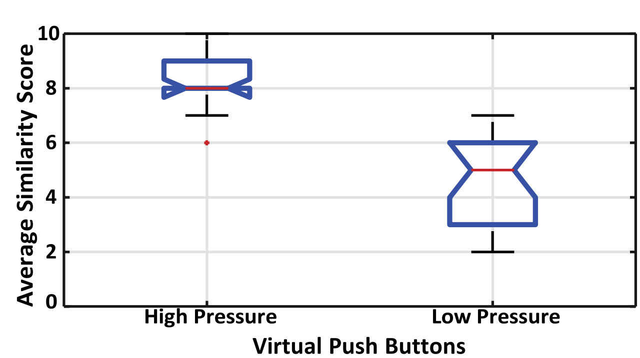

Fig. 15. Similarity score of the two virtually overlaid push buttons against a real push button.

aspects may affect the user experience.

This experiment was broadly divided into three sub-categories; realism, display fidelity, and usability. Each one of these categories touches upon a different aspect of the user experience.

6.3.1. Participants and stimuli

The same 11 participants took part in this experiment. The stimuli used in the previous two experiments were used in this experiment.

6.3.2. Procedure

The participants wore the device on their index finger and interacted with all the virtually overlaid textures and the buttons. The real textures and buttons were also available for interaction. This time, the vision was not blocked. A paper containing pictures of the real textures and buttons was prepared, and the virtual haptic textures and buttons were overlaid on them. The pictures were provided to enhance the sense of immersiveness and realism. The participants were free to interact with the virtually overlaid textures and buttons for as long as they wanted using their preferred method of interaction. They were given a list of questions to answer based on their interaction. They were free to interact again during the course of filling up the questionnaire. Each question was answered on a seven-point Likert scale. In all the cases, a higher value on the scale meant a more positive response, while a lower value meant that the participants were not satisfied with that particular aspect.

6.3.3. Data analysis and results

The data from all the participants were averaged, and the mean values along with the standard deviation are presented in Fig. 16. It can be seen that users found the realism and usability aspects of the system to be the most appealing. One user complained about perceiving a delay in the response of the device but the majority of them had a rather smooth experience.

The questionnaire was divided into three different categories to test the various aspects of the device, i.e., the realism, display fidelity, and usability. First, how faithfully can the proposed device recreate the texture and button feedback? Most of the participants remarked that their interaction with the haptic aspect of the environment seemed natural, and this is also reflected in the ratings from the questionnaire.

Second, the participants were questioned about the form factor of the overall output from the system, i.e., the weight of the actuator, delay in feedback, or any other chinks that made the experience unnatural. Judging by the score from the questionnaire and participants' responses after the experiment, most of them seemed satisfied with the system. However, one participant did complain about a slight mismatch between action and its response. This might be accredited to some loose wiring, occlusion in tracking, or other hardware issues, given that it did not happen during any of the other participants' experiences or none of them noticed it.

Third, it was important to find out how comfortable the participants felt during the whole interaction. From an experimenter's point of view, it was noticed that participants adopted the device very smoothly. After some initial guidance about handling the device, all the participants were easily able to interact with the virtual textures and buttons.

7. Conclusion

In this paper, we introduced a new finger-shaped wearable multimode feel-through tactile display operated by pneumatic actuation. We also examined the physical characteristics of the haptic device with a series of qualitative and quantitative experiments.

To find out device applicability in the haptic domain, we implemented haptic augmented reality scenarios where we exploited the device capabilities by rendering various virtual textures on a real surface, including button click effects. The performance of the system was further evaluated by the perceptual user experiments. Three different experiments were performed to compare the similarity between real and virtually rendered textures and buttons. Overall, the results demonstrated the effectiveness of the proposed device and its efficacy in the haptic augmentation scenarios. In particular, we were able to confirm the advantage of merging real and virtual feedback.

Nonetheless, our current implementation has some limitations. This device can generate only one kind of feedback at a time. However, this issue can be solved by a new miniaturized multicavity design of the end-effector but at the cost of the enhanced hardware setup.

In the future, we will extend the concept of pneumatically actuated wearables with a focus on various body parts, realizing full-body haptic augmentation. In order to facilitate the multimode haptic feedback, we will also introduce other types of haptic feedback using pneumatic actuation, e.g., stiffness and stickiness of materials, and explore geometry of the object.

CRediT authorship contribution statement

Aishwari Talhan: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Project administration, Writing - original draft, Writing - review & editing. **Sanjeet Kumar:** Software, Validation, Formal analysis, Writing - review & editing. **Hwangil Kim:** Software, Validation, Formal analysis, Data curation, Visualization. **Waseem Hassan:** Investigation, Data curation, Visualization, Writing - review & editing. **Seokhee Jeon:**

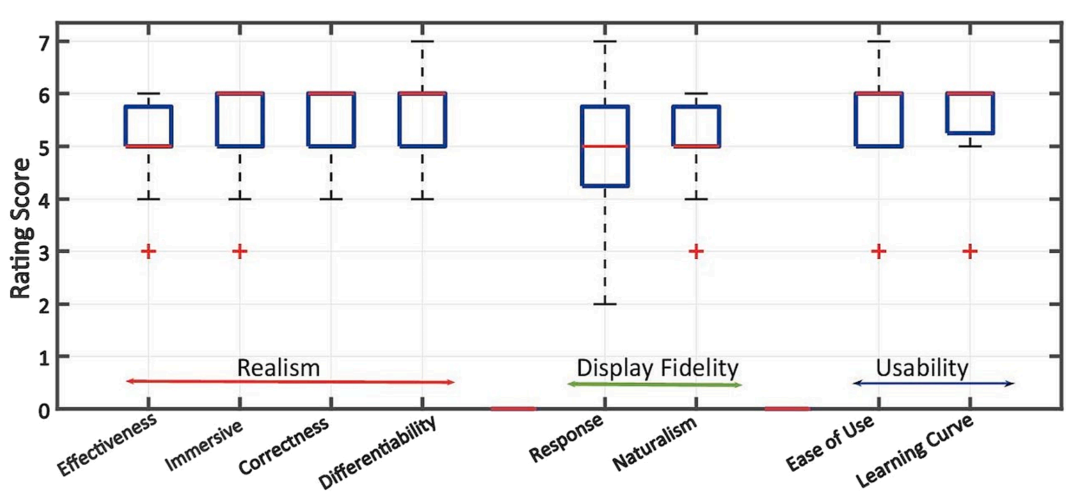

Fig. 16. Rating score from the user experience study.

Resources, Supervision, Project administration, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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