IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received November 26, 2019, accepted December 11, 2019, date of publication December 23, 2019,
date of current version January 3, 2020.

Digital Object Identifier 10.1109/ACCESS.2019.2961430

Tactile Ring: Multi-Mode Finger-Worn Soft Actuator for Rich Haptic Feedback

AISHWARI TALHAN, HWANGIL KIM, AND SEOKHEE JEON
Department of Computer Science and Engineering, Kyung Hee University, Yongin-si 17104, South Korea

Corresponding author: Seokhee Jeon (jeon@khu.ac.kr)

This work was supported by the Preventive Safety Service Technology Development Program funded by the Korean Ministry of Interior and Safety (MOIS) under Grant 2019-MOIS34-001.

ABSTRACT This paper presents a novel finger-worn actuator capable of generating three distinctive haptic effects: static pressure, high-frequency vibration, and an impact. Our new design makes this multi-mode feedback with a single actuator possible in a small form factor. A ring-shaped air bladder made with soft silicone is inflated or deflated to generate feedback on the finger. The airflow is controlled by a pair of air valves connected to a compressed air tank. Besides static pressure, the actuator can generate high-frequency vibration with high acceleration and crisp impact feedback due to fast controllability of the valves with a strong air source and a lightweight bladder membrane. In addition, our special design and fabrication of the bladder – a combination of stretchable and non-stretchable membrane layers in the ring – allows for stronger feedback. Rendering algorithms for three kinds of feedback are also presented. The performance of the system and the characteristics of the feedback are thoroughly examined using a series of measurement experiments, revealing that the system can generate a static force up to 6.3 N, the vibration up to 2.2 g magnitude and 250 Hz frequency, and an impact with less than 5 ms of latency. The whole system weighs only 255 grams (4.5 grams for the actuator and 250 grams for the controller). Finally, we demonstrate the wearability of the system by integrating the modules into a self-contained haptic device in the form of a wristlet.

INDEX TERMS Actuator, augmented haptics, haptics device, soft haptics, pneumatic, impact, static pressure, multi-mode, tactile feedback.

I. INTRODUCTION

Haptic feedback increases the realism and immersiveness of a VR/AR-based system. Haptic signals are delivered to a user in two different forms; 1) kinesthetic feedback, which is related to the perception of position, movements, and forces [1], and 2) tactile feedback, which is associated with the perception of vibration, pressure, or shear force through the skin. Both kinesthetic and tactile information are simultaneously present when exploring an object. On the one hand, a haptic device for kinesthetic feedback needs a large-scale mechanical structure to provide perceptually meaningful force and movement to a body part. On the other hand, haptic devices for tactile feedback usually have a small form factor due to the high sensitivity of tactile receptors in human skin. This allows us to easily make a tactile haptic device wearable or holdable [2], eventually increasing the usability of a VR/AR system.

The associate editor coordinating the review of this manuscript and approving it for publication was Yangmin Li.

In most cases, a wearable/holdable tactile feedback device uses a single kind of actuator to produce a single type of feedback. For instance, many game controllers only provide vibrotactile feedback. Meanwhile, highly realistic and immersive VR/AR systems require a complete set of diverse tactile feedback. For example, when exploring an object using a finger, the finger simultaneously senses high-frequency vibrations and quasi-static pressure, and the brain merges the two sensations to invoke the feeling of the object. The lack of one of the physical signals may seriously deteriorate fidelity. This may be one of the reasons why current wearable haptic interface technology for VR/AR systems is not at the same level as visual interfaces.

Combining multiple actuators that provide a different kind of feedback provides a straightforward solution. However, covering a small sensitive area with multiple actuators as a single end-effector is not a trivial task. Besides, using various hardware makes the system bulky and decreases usability, especially when wearability is the main concern.

Our approach to overcome these limitations is to use a soft actuator operated by pneumatic control. We made a soft bladder in a ring-shape that can be worn on the finger. By controlling the amount of air in the bladder, a strong static pressure can be generated. This set up can also transmit other types of stimuli.

The soft bladder is made up of a light-weight and flexible material that allows the layer to move faster with a small amount of pneumatic actuation energy. By fast controlling the air valve connecting an air source and the bladder, high-frequency vibration and even impact can be rendered using a single actuator. We carefully designed a system to maximize the feedback performance, resulting in a 6.3 N static pressure, approximately 2.2 g vibration, and very crisp impact feedback. To our knowledge, this multi-mode actuator providing three distinctive feedbacks is new, and in particular, generating high-frequency vibrotactile feedback using pneumatic actuation has not achieved previously. The noise generated by a conventional air compressor and the size of pneumatic assembly might be the significant concerns; the simple solution to reduce the size and noise is to use a small and portable compressed air tank.

The paper is structured as follows. Section II presents an overview of the related literature of wearable and multi-mode tactile feedback devices. Section III describes the concept and design of our haptic actuator. Section IV describes the fabrication processes of the soft ring-shaped actuator, followed by Section V, which provides details about the pneumatic control algorithm. Section VI examines the characteristics of the generated feedback through a series of measurement experiments. Section VII discusses the wearability and application of our system. Finally, Section VIII concludes the paper and offers remarks.

II. RELATED WORK

For a haptic actuator to be worn or attached to a body part, it should be small and lightweight. This requirement limits the kind of haptic feedback in wearable haptics to vibrotactile feedback only since perceptually significant vibrotactile feedback can be generated even by minimal mechanical movement or acceleration. For this purpose, many actuation technologies with a small form factor have been used in the field of wearable haptics.

One of the simplest vibrotactile actuator technologies is the rotary electromagnetic actuator: vibration is generated by rotating an eccentric mass, which creates relatively significant acceleration with a small size [2]. However, it is not frequently used nowadays since the frequency and amplitude cannot be controlled independently.

The second type is a linear electromagnetic actuator, which produces tactile vibrations by making a magnetic mass linearly oscillate to generate a wave of electromagnetic fields via electronic coils, e.g., C2 tactor (Engineering Acoustics, Inc.), Tactaid, and the Haptuator (Tactile Labs, Inc.) [3], [4]. Actuators in this category are considered well-balanced in terms of size and power, and the amplitude and frequency can be controlled independently. However, the spring-based mass oscillation can limit the frequency bandwidth of the feedback.

The last category, non-electromagnetic actuators, usually utilize piezoelectric phenomenon to generate vibration. This vibrotactile display applies high electric voltage to ceramic material or elastomer to create deformation via piezo effect, e.g., [5] and [6]. This type of actuator usually has a relatively larger frequency bandwidth but suffers from a small amplitude and the need for a very high input voltage, e.g., up to 3.5 kV, which prevents it from being used in wearable applications.

This paper is concerned with pneumatic actuation to generate tactile feedback. Pneumatic actuation uses controlled air pressure to travel, expand, and inflate or deflate the mechanical elements that create the haptic effects in the end-effector. Although its high power-to-weight ratio makes it optimal to be worn, not many investigations into this aspect have been made. Among a few examples, Rutgers Master II uses pneumatic pistons to generate force feedback up to 16 N to the fingers [7]. Fan et al. generates monotonic pressure patterns for a lower limb prosthetic, which rely on pneumatically controlled balloons embedded in a cuff [8].

A few works tried to integrate pneumatic actuators with other tactile/force feedback techniques to generate multi-mode feedback in a single system. For instance, Premarathna et al. proposed a soft tactile multi-mode display that uses pneumatic actuation to generate force feedback, while a voice coil is used to create vibrotactile feedback [9]. Another example is a portable, low-cost haptic glove that provides both force and tactile feedback through a pneumatic piston-powered exoskeleton structure and pneumatic balloons embedded at the joint of fingers [10]. Recently, a pneumatic actuated bracelet for upper limb amputees was proposed [11]. The authors used pneumatic actuation for creating force feedback and vibrotactile feedback, producing an average amplitude of 12.5 N at 70 kPa with a bandwidth up to 70 Hz.

The focus of the present work is to generate multiple kinds of haptic feedback through a single actuation technique and single end-effector to enrich feedback in an AR/VR environment. Particular attention was given on creating high pressure and high-frequency vibration as well as impact feedback via a simple small soft ring. To our knowledge, generating this multi-mode feedback with a single actuation technique has not been attempted yet. In particular, our system is the first to reach a high frequency up to 250 Hz through pneumatic actuation. Furthermore, by using a compact compressed air tank and wireless RF communication technology, our system is entirely portable, while still preserving the high power of pneumatic-based actuation, which has not been achieved before.

III. ACTUATOR CONCEPT AND DESIGN

In this study, our focus is on developing a wearable haptic device for the most sensitive and most used body part for

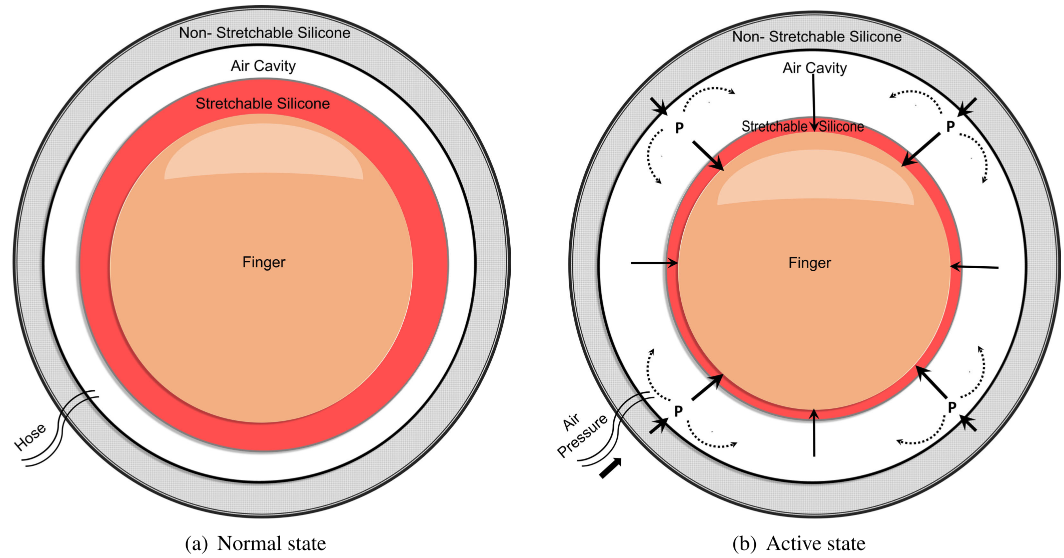

FIGURE 1. The conceptual design of the actuator: (a) the normal (inactive) state and (b) pressurized state (active).

tactile perception: the finger and fingertip. After reviewing multiple wearable haptic systems, we found critical requirements that a hand wearable system should satisfy for the system to be practically used:

1) easy to wear
2) light weight (enough for usability)
3) completely portable
4) richer and stronger feedback (not just vibration or static pressure only).

For the first requirement, a ring metaphor was chosen to make putting it on and taking it off extremely simple and fast. This additionally allows covering the most sensitive body parts of a user. For the second requirement, wearability is increased by manufacturing the light-weight ring using flexible silicone, so that firm attachment is obtained when worn. The third requirement is achieved using a compact compressed CO_2 tank as an air source by embedding a core pneumatic control module into a small microcontroller worn at the wrist. The fourth requirement is the major concern of this work. We made a donut-shaped bladder manufactured with soft silicone. In particular, the inner membrane of the donut that would be in contact with a user's finger skin is made with stretchable silicone while the outer membrane of the donut is made with non-stretchable silicone (see Fig. 1). When compressed air blows into the chamber between the two membrane layers, only the inner stretchable membrane will expand, with the inside air pushing inward against the contacted skin and consequently generating pressure feedback to the user. The outer non-stretchable membrane holds the shape and size.

This design has several benefits. First, multi-mode operability allows three modes: high static pressure, high-frequency tactile feedback, and fast-changing impact. This becomes possible because the actuator is soft and the moving part is light-weight (negligible inertia), has fast valve control,

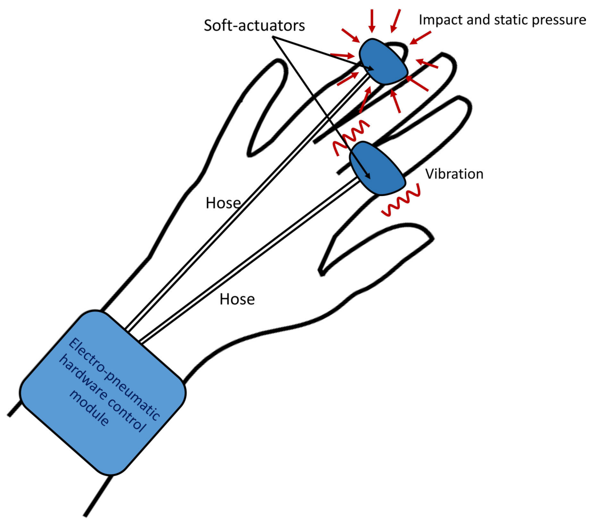

FIGURE 2. Wearable concept of the system.

and uses of strongly compressed air. Second, stronger haptic feedback allows the pressurized air controls the inner "Stretchable Silicone" layer, while the outer "Non-stretchable" layer remains unchanged (see Fig. 1 (b)). This one sided blowing of air doubles the amplitude of the feedback and increases the contact area due to the ring shape and flexibility of the end-effector. Additionally, highly compressed air reduces the response time, allowing a perceptually negligible delay and high frequency vibration. Third, the user will feel the rich and active haptic feedback via a comfortable, soft, and gentle piece mounted on the finger. We selected soft-silicone rubber, since it satisfies all the aforementioned requirements.

Fig. 2, shows the overall concept of the system, where the various wearing positions of ring-actuator and wearable electro-pneumatic control unit are combined.

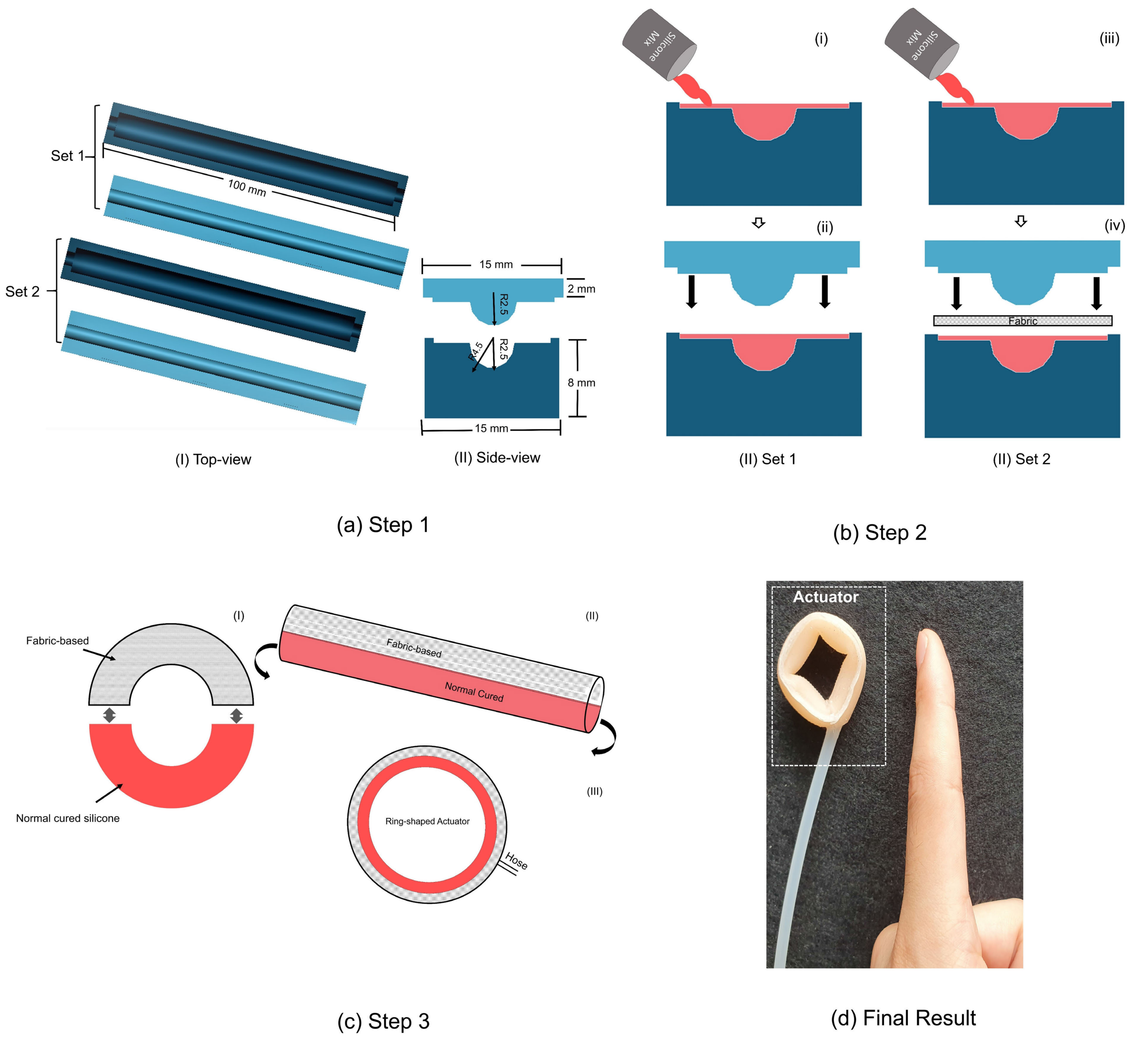

FIGURE 3. **The fabrication process of the actuator: (a) 3D-printed mold sets for two membranes, (b) Step 2: Silicone casting process for stretchable and non-stretchable membranes, (c) Step 3: the process of final assembly; connecting the two splits and inserting the hose, and (d) the final fabrication result where a finger is for size reference.**

IV. FABRICATION OF ACTUATOR

This section details the process for manufacturing the soft ring actuator.

A. MATERIALS

The main material of the membranes used in the actuator is Ecoflex 00-50 or 00-30 platinum-based cure silicone (smooth-on, Inc.). It is soft, skin-safe, and has a high tear strength even when very thin layer [12]. The mechanical properties of the material are given in Table 1.

B. FABRICATION OF STRETCHABLE AND NON-STRETCHABLE MEMBRANE

Our design of the actuator requires two different membranes: stretchable and non-stretchable. The stretchable membrane can be easily manufactured through the regular mixing, molding, and the curing processes of the Ecoflex silicone. To turn the Ecoflex silicone into non-stretchable silicone while preserving its flexibility in shape change, we embed a cotton fabric into the silicone membrane, as introduced in our previous publications [13], [14].

We experimentally tested the behavior of both silicone membranes. For the two silicone materials (Ecoflex 00-30 and 00-50), membranes were manufactured using the process introduced in the next section (see Section IV-C),

TABLE 1. **Mechanical characteristics of two silicone materials.**

Type	Young modulus	Shore hardness	100 % modulus
Ecoflex^{TM} 00-30	0.1694 MPa	00-30	At 10 Psi
Ecoflex^{TM} 00-50	0.2642 MPa	00-50	At 12 Psi

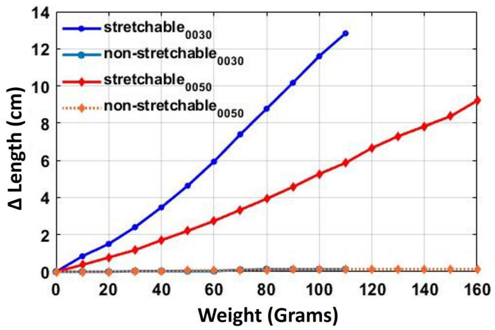

FIGURE 4. Stretching characteristics of the fabricated membranes.

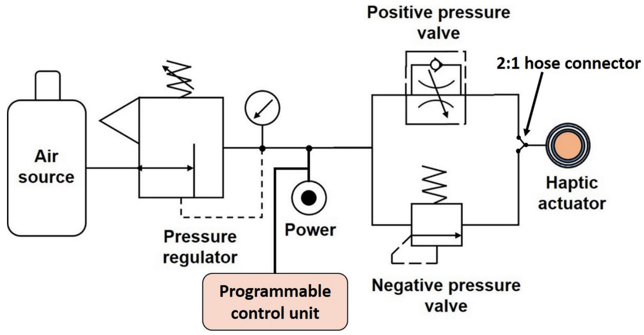

FIGURE 5. Pneumatic control module.

giving us four different samples. For each sample, one end of the membrane was hung downward at the fixed height. Then, a 10-gram mass was attached at the other end, and the change in length was recorded. We kept adding additional 10-gram masses and measuring the length change until the length of the stretchable sample doubled. The results are shown in Fig. 4. It is clearly seen that the membranes with embedded fabric show negligible planer strain compared to the normal membrane.

C. FABRICATION OF RING ACTUATOR

The fabrication process of the ring actuator includes three primary steps: i) mold construction using a 3D printer to make two identical cylinder halves, ii) casting of two halves, one for the stretchable membrane and the other for the non-stretchable membrane, and iii) closing the two halves and inserting a hose. The whole fabrication process is summarized in Fig 3.

The first step is to construct molds for the casting. The casting molds are 3D-printed (Zortrax M200; Zortrax S.A.). The dimensions of the molds are shown in Fig. 3 (a). Note that the length of the printed mold is set to 100 mm, but is subject to change depending on the thickness of the target user's finger. Generally, 65 to 77 mm length fits the user's finger with an average finger thickness.

The second step is the casting of membranes in the desired shape. The casting process begins with mixing part A and part B of the silicone rubber compound (Ecoflex, smooth-on, Inc.) in equal amounts [15]. This is followed first by the degassing process of the mix using a vacuum pump and vacuum chamber. Then, the silicone mix is poured into the first set of molds for the stretchable membrane. For the non-stretchable membrane, we prepare a fabric piece (Boryung; ATomild Premium, Korea.) cut with the same dimensions as the size of the mold. Then, we pour the silicone mix in to the second half of the mold (set 2), implant the fabric on the mix, and pour the silicone mix on the fabric again (see Fig. 3(b)). Finally, for both mold sets, the molds are closed by tight-fitting the mold cover. These two halves are kept on rest for 4-6 hours in room temperature to be cured.

The third step is to achieve the ring shape by joining the two halves together. Two halves of silicone are carefully removed from the mold and glued to each other using a silicone rubber adhesive, making a single long soft-silicone-tube (see Fig. 3(c)). Then, the two ends of this flexible tube are precisely and carefully glued together. Note that the alignment of the boundaries between stretchable and non-stretchable should be preserved. Also, the stretchable layer should be kept as an inner side and vice versa. After all the adhesives have settled, a hose (320 mm) is plugged into the outer membrane to make the end of the hose reach the air cavity and glued firmly.

An example of the fabrication result is shown in Fig. 3 (d). The total weight of the actuator was about 4.5 grams. The durability of the actuator is high enough: multiple actuator samples were tested for six months; no teardown or shape changed has been observed. Nevertheless, a care should be taken to avoid the punctuation of the membrane by sharp objects such as a needle.

V. CONTROL AND EFFECTS RENDERING

Physical haptic feedback from the actuator is created by changing the amount of air inside the bladder of the actuator. The amount of air in the bladder is controlled by two solenoid pneumatic valves: one positive valve (SC0526GC; Skoocom Technology Co., Ltd) connecting a compressed CO_2 cartridge to the bladder and one negative valve (SC0526GF; Skoocom Technology Co., Ltd). These two valves are coupled at one end of a 2:1 ('Y'-shaped) hose connector, whereas a soft-actuator is attached to the another end, such that opening the positive valve increases the amount of air in the bladder while opening the negative valve releases the air (see Fig. 5). These valves are operated using a 6V DC power supply.

As an air source, we used a CO_2 cartridge with a pressure regulator. A CO_2 cartridge is light-weight (12 gram), portable, powerful enough to make fast changes in the pressure, and noiseless compared to other air sources, e.g., an air compressor. The base pressure from the tank can be set by manually controlling the dial at the regulator. Throughout this paper, we use the base pressure of 5 psi or 10 psi, which were found as optimum in our tests.

The control of the two solenoid valves is achieved by a microcontroller board (Arduino Nano board) with custom-made MOSFET transistors. Two digital output ports of the control board are used to send valve on and off commands. The control board has a wireless RF connection with a PC

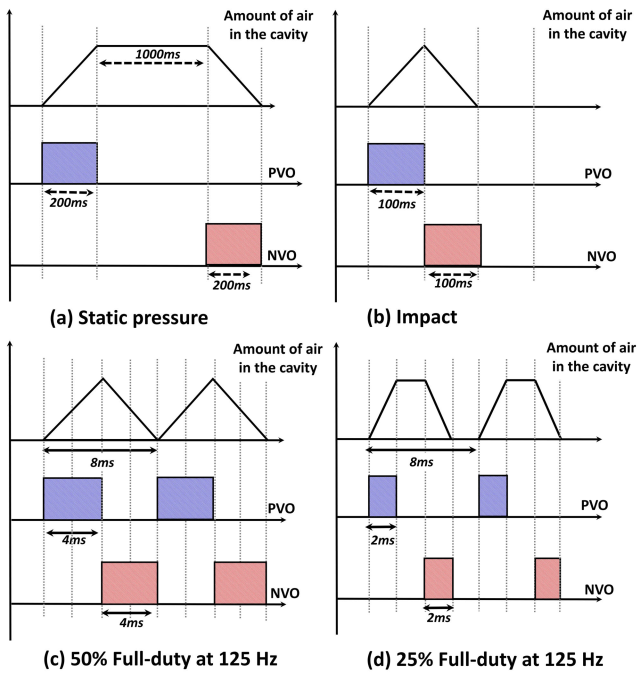

FIGURE 6. Valve control examples and corresponding bladder size changes for different kinds of feedback.

where actual rendering is performed based on the interaction data from the user. Note that the control of the valves is limited to either full opening or full closing. There are valves that allow multiple degrees of opening, but we choose the current valve model due to its speedy response and small size for portability. The complete set up weighs 255 grams, which is half of the acceptable limit for hand wearable interfaces, as suggested in [16].

Three distinctive haptic effects can be generated as follows.

1) Static pressure: Inflate the bladder by opening the positive valve and then hold the air by closing all valves. The amount of static pressure is determined by the opening duration of the positive pressure valve. (See Fig. 6 (a) as an example of 1-second static pressure with a 200 ms opening duration.).
2) Impact feedback: Inflate the bladder by opening the positive valve. Then, immediately close the positive and open the negative simultaneously to release the air (see Fig. 6 (b)). From our experience, a 100 ms opening created crisp impact feedback with reasonable strength for Ecoflex 00-30 and a base pressure of 10 psi. The variation of impact can be made by adjusting the opening duration.
3) Vibration: Open and close the positive and negative valves alternately (see Fig. 6 (c) and (d) as examples of 125 Hz vibration with different amplitudes). The duty cycle (the proportion of opening duration over the whole cycle) of the valves determines the amount of displacement, i.e., the amplitude of the vibration while the frequency of the opening alternation decides the frequency of vibration. For the synchronized opening of the positive and negative valves, we set the duty cycle of the valves cannot exceed 50%. In addition, for the same reason, we set the opening duration of the negative valve the same as that of a positive valve, which is different from the cases of static pressure and impact rendering. Once a desired frequency and duty cycle is determined, the duration of opening T for both valves can be derived by equation (1).

$$T = \frac{1000 \cdot \alpha}{f} \tag{1}$$

where, α is the desired duty cycle, and f is the desired frequency. The control resolution of the valves determines the highest frequency that the system can generate. For instance, the smallest opening duration of the solenoid valve used in our system is 2 ms, and thus the highest frequency that the system can generate is 250 Hz.

VI. CHARACTERIZATION OF ACTUATOR

In this section, the characteristics of the actuator are evaluated. A series of measurements was conducted, and the results were analyzed. We first characterized the frequency response of the actuator, followed by the characterization of the static force response and the impact response.

In all the experiments, two different actuators made with two different Ecoflex materials (00-30 and 00-50), and two base air pressure (i.e., 5 and 10 Psi) were used. In general, the performance of a pneumatic system largely depends on various parameters such as i) the base air pressure of the air source, ii) mechanical properties of the material for the membrane, and iii) temporal control resolution of pneumatic valves. Experiments in the section are also intended to determine the effects of the first two parameters.

A. ACCELERATION RESPONSE IN VIBRATION RENDERING

To analyze the frequency characteristics of the actuator, 21 different frequencies were rendered, i.e., 1, 2, 2.5, 3, 4, 5, 6, 25, 7.8, 10, 12.5, 15, 30, 31, 50, 55, 62, 71, 83, 100, and 250 Hz, using the algorithm mentioned in Section V. For all of these conditions, the duty cycle was 50%. The magnitude changes are measured under different silicone actuators and base pressures for the frequencies mentioned above.

1) MEASUREMENT SETUP AND PROCEDURE

The setup for this experiment is illustrated in Fig. 7. An accelerometer (ADXL335; Analog Devices, Inc.) was attached at the inner surface of the ring for the measurement. A data acquisition device (NI-DAQ 6009; National Instrument, Inc.) with the Analog Input Recorder tool in Matlab (The Mathwork, Inc.) was used for recording data. We calibrated the accelerometer before every experiment. For every frequency, 5-second acceleration data were recorded in a 1 kHz sampling rate. The actuator and necessary modules were put on a plastic cylindrical tube support to minimize the undesired effects from the rigid support.

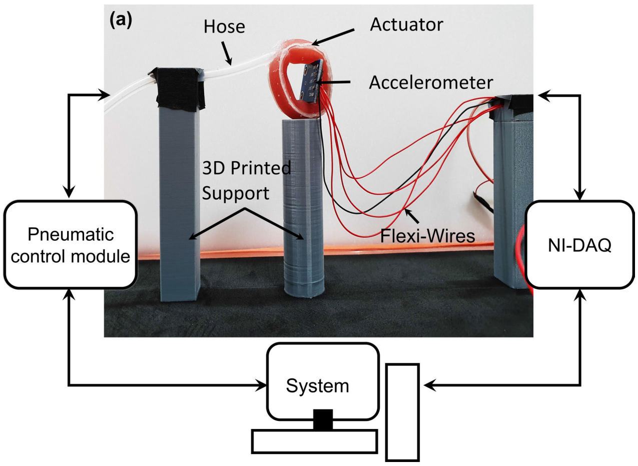

FIGURE 7. An experimental setup for characterizing the frequency response and magnitude.

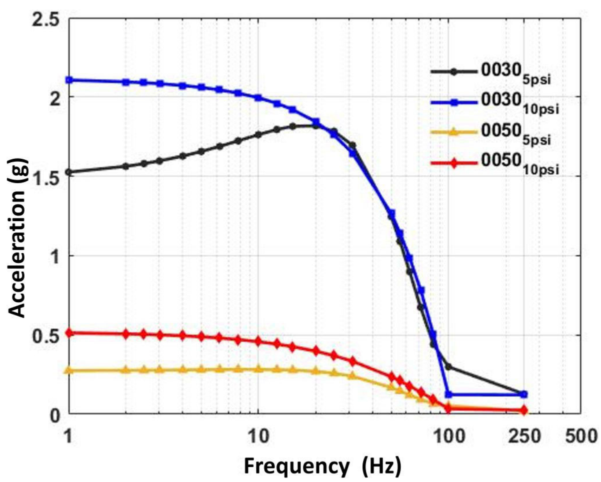

FIGURE 8. Measured acceleration amplitude against frequency (Hz).

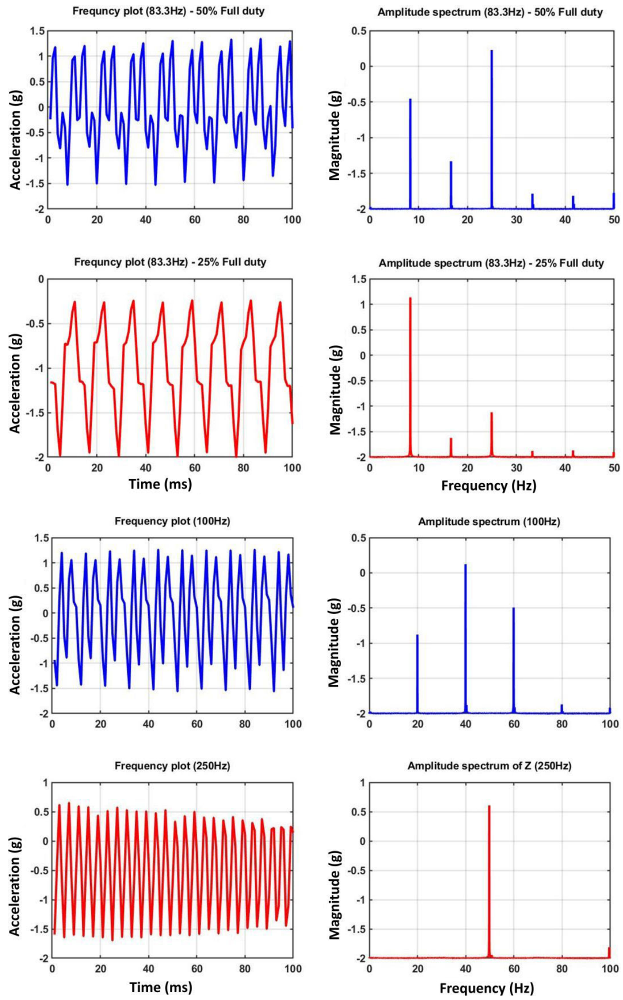

FIGURE 9. Examples of rendered acceleration feedback in the time and single-sided frequency domains.

2) RESULTS AND DISCUSSION

Fig. 8 shows the measured acceleration under various conditions. The actuator made of Ecoflex 00-30 exhibits much higher acceleration than the Ecoflex 00-50 actuator for both the base pressures of 10 psi and 5 psi. Maximum acceleration performance was achieved until 50 Hz, and then the maximum amplitude decreases as the frequency increases until 250 Hz.

Maximum acceleration performance was achieved until 50 Hz, and the maximum amplitude decreases as frequency increases until 250 Hz. However, the amplitude at 250 Hz (0.12 g converted into 1.17 m/s^2) is still quite higher than human vibration perception absolute threshold at 250 Hz (ranges from 0.08 to 0.1 ms^{-2} in [17], [18]), which implies that rendering at 250 Hz is still usable.

Note that different from other vibrotactile actuators, our actuator still exhibits a very high acceleration amplitude at low frequencies down to 1 Hz.

As examples, actual acceleration measurements in the time domain and frequency domain space are plotted in Fig. 9.

B. PRESSURE RESPONSE IN STATIC PRESSURE RENDERING

This section characterizes the pressure feedback in the static pressure rendering mode. In static pressure rendering mode, the control variable is the duration of the valve opening, and thus we measure the pressure magnitude from the actuator while varying the positive valve opening duration. The inverse of this measurement is later used for precise control of the static pressure.

1) MEASUREMENT SETUP AND PROCEDURE

Fig. 10 depicts the experimental setup for force measurement.

To simulate the human finger, a plastic cylinder (ø= 15 mm) was inserted in to the actuator.

Two FlexiForce A201-medium versions (0-25lb) force sensors (by Tekscan, Inc., USA.) were placed between the actuator and the cylinder on opposite sides. The force sensing resolution of the sensor was 0.1 N (with 10-bit AC-DC converter), which, we believe, enough accuracy, considering that the measurements are for static pressure and to find trends in force. The accuracy is also quite comparable to human

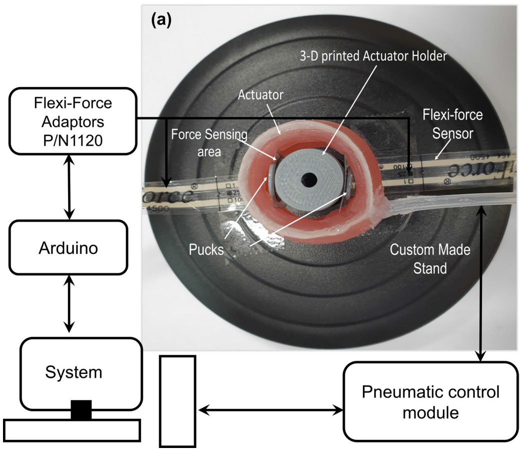

FIGURE 10. Experimental setup to measure the force response of the actuator.

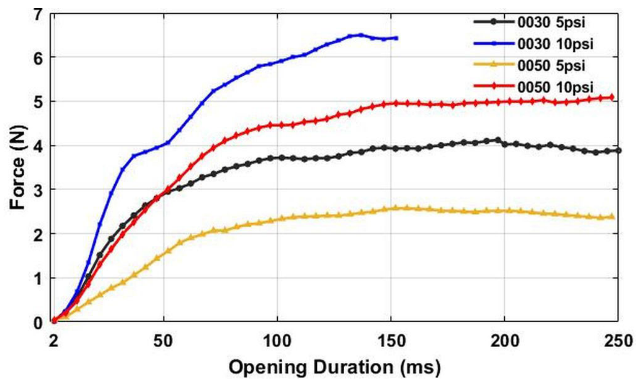

FIGURE 11. Rendered force vs. positive valve opening duration.

force-sensing resolution. To minimize the effect of bending of the sensor and for stable measurement, a rigid puck was placed between the sensor and the actuator [19]. The sensor was calibrated before every measurement. session [20].

Force measurements were performed after opening the positive valve for a predetermined duration. The opening duration was changed from 2 to 250 ms with a 5 ms step size. The final results were computed after taking the average of three measurements for each data point to minimize the effect of sensing noise.

In addition, we characterize the pressure responses during air release. First, for each condition, the positive valve is opened for 20 ms. Then, a similar procedure as above was taken except that the negative valve is opened for predetermined steps in this time.

2) RESULTS AND DISCUSSION

Fig. 11 shows the force magnitude changes vs. valve opening duration. As expected, a longer opening duration gives a higher force magnitude, and a higher base pressure with a softer membrane exhibits higher increases in the pressure. However, the increase was stopped at 150 ms duration and saturated. This is partially due to the pressure limit that pneumatic assembly with an end-effector can hold. Another reason is that after 150 ms, the pressure is not used to increase anymore but instead used to stretch the flexible membrane laterally, and thus used to increase the contact area. This may largely depend on the material used to manufacture the membranes.

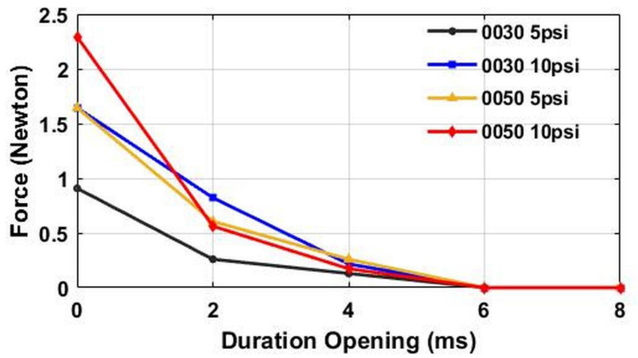

FIGURE 12. Force changes against the duration of the negative valve opening.

Overall, within 150 ms, the actuator can generate up to 6.3 N force at the finger, which is more than enough for most haptic related applications [21].

Note that the measurement of Ecoflex 00-30 at 10 psi is stopped at 150 ms since the membrane becomes damaged after 150 ms. This should be considered in the actual rendering algorithm.

For air release, the measurements are plotted in Fig. 12. The changes in force are much faster during air release compared to air inflation. Within 8 ms, the air is already fully released. This is partially due to the fast operating characteristics of the negative valve.

C. IMPACT RESPONSE

For impact rendering, the immediacy and the strength of initial transient acceleration of the feedback are two important physical characteristics that affect the perceptual quality of the feedback. This section examines our actuator and rendering system regarding these two characteristics.

1) MEASUREMENT SETUP AND PROCEDURE

To examine the immediacy and strength of the feedback, a step command is applied to the actuator, and the latencies between the command and initial acceleration as well as the waveform of the initial acceleration are measured.

The same measurement setup as Fig. 7 was used. For measurement, we followed the impact rendering algorithm introduced in Section V. We first applied a 6-volt step input to the positive valve for 100 ms, then the negative valve was opened for 100 ms. The acceleration signals were measured during the two openings at 1 kHz.

2) RESULTS AND DISCUSSION

Fig. 13 illustrates one of the measured response times during impact rendering. In most measurements, the time interval between the beginning of the positive valve open command and the beginning of the acceleration was about 5 ms.

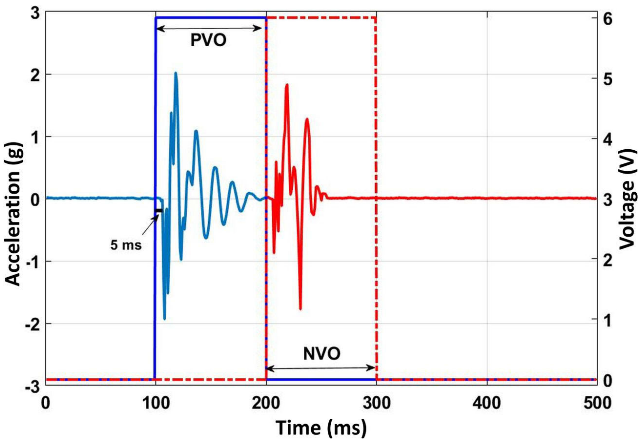

FIGURE 13. An example of the measured acceleration feedback during impact rendering.

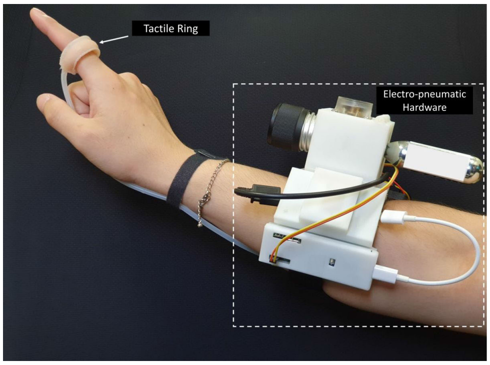

FIGURE 14. Final demonstration of the wearability of the system.

Note that the response time in a pneumatic system highly depends on the performance and characteristics of the hardware parts used in the system, such as the temporal resolution of the valves, electro-pneumatic delays, the physical properties of hose material, and the length of the hose. The aspects related to hose are often overlooked and increase the delays in the pneumatic system; for example, excessive length of the hose between the actuator and valves may alter the cycle time or force at the end-effector [22], [23].

In our current implementation, this low latency result is possible mainly due to the solenoid valve we used. The electromagnetic mechanism of solenoid allows speedy response time, and the specific valve in our system exhibits 2 ms latency according to the specification. The use of a high-pressure CO_2 tank is also one of the factors that enable this low latency response. On the valve opening, air travels at its highest speed to the chamber. A light-weight and thin membrane of the actuator can be another positive factor for the fast response.

Overall, we speculate that a 5 ms delay is perceptually negligible. The haptics literature reports that the threshold of temporal asynchrony perception for tactile events ranged from 27 ms to 71 ms, depending on various aspects, such as the modality and time at which two modalities are involved, and the order of stimulation [24]. For instance, it is reported that in visual-tactile stimuli, a delay of 71 ms is permissible when visual stimuli presented first [25], while a delay of 53 ms is acceptable in the opposite case [24]. Wundt found that the human temporal perception threshold of simultaneity perception is 27 ms for two intramodal (same modality) events, whereas the perception threshold for visual-haptic simultaneity is 45 ms for asynchronous stimuli [26]. Additionally, the recent guidelines suggest that a tactile feedback latency of 5 to 50 ms is acceptable in simultaneous finger touching and the touch screen [27]. Based on this information, a 5 ms latency in our system can be considered perceptually negligible.

VII. WEARABLITY AND APPLICATION

Fig. 14 depicts our final prototype worn by a user. Many special efforts were made to make the whole system wearable. In particular, using a small CO_2 air tank significantly reduces the size and weight of the system. All the control modules are self-contained. For instance, a miniaturized battery powers the control board that relays the command from the contents PC to the actuator through RF communication. We 3D-printed a special wristlet, where all the control modules are firmly attached.

The potential applications of this haptic actuator are spatial guidance, assertive alerts, virtual games, and sensory substitutions. With this setup, we implemented a VR based application. This demonstration in [28] includes the rendering of haptic surface textures. We rendered different vibrations when stroking various textured surfaces. In addition, through impact rendering, button clicks were simulated in a virtual environment. We also received subjective comments from the participants. One participant commented that "These textures feel so real," another participant mentioned that "I like that button clicked-impact effect," and another considerable comment is, "This actuator is so soft, simple, and effective too."

VIII. CONCLUSION

This work examines the feasibility of using a silicone bladder operated pneumatically as a multi-mode haptic display. We successfully demonstrated that the proposed concept can generate multiple kinds of distinctive feedback with high performance. We also implemented the concept with a small form factor, demonstrating the wearability of this approach.

As future work, we will investigate the potential by improving our rendering algorithm. In the current implementation, only one kind of feedback can be generated at a time. However, it is physically possible to generate multiple kinds of feedback simultaneously by carefully designing and testing the rendering algorithm. We are also planning to further examine the perceptual characteristics of the feedback through extensive psychophysical experiments.

Nonetheless, the current implementation of the system has some limitations. Two valves are needed for each actuator, and the scalability of the system to multiple fingers is somewhat limited in terms of the size and weight. Further, the refillable air tank is not permanent; lasts for 20 min under continuous usage, e.g., vibration measurement experiments, and lasts for about one hour under usage in a regular interaction scenario.

The drawbacks of conventional pneumatic actuation, e.g., bulky and noisy air source, are partially overcome in our work, and there are many benefits of using this approach. For instance, a soft end-effector is skin-safe and can stimulate a large area of the skin. This characteristic is beneficial if stimulation on a very sensitive part of the skin is needed. We hope that the present work inspires other haptic researchers to utilize soft actuators with pneumatic control in the field of haptics.

REFERENCES

[1] H. Culbertson, S. B. Schorr, and A. M. Okamura, "Haptics: The present and future of artificial touch sensation," *Annu. Rev. Control, Robot., Auton. Syst.*, vol. 1, pp. 385–409, May 2018.

[2] S. Choi and K. J. Kuchenbecker, "Vibrotactile display: Perception, technology, and applications," *Proc. IEEE*, vol. 101, no. 9, pp. 2093–2104, Sep. 2013.

[3] B. J. Mortimer, G. A. Zets, and R. W. Cholewiak, "Vibrotactile transduction and transducers," *J. Acoust. Soc. Amer.*, vol. 121, no. 5, pp. 2970–2977, 2007.

[4] H.-Y. Yao and V. Hayward, "Design and analysis of a recoil-type vibrotactile transducer," *J. Acoust. Soc. Amer.*, vol. 128, no. 2, pp. 619–627, 2010.

[5] M. Matysek, P. Lotz, and H. F. Schlaak, "Tactile display with dielectric multilayer elastomer actuators," *Proc. SPIE*, vol. 2009, Apr. 2009, Art. no. 72871D.

[6] I. M. Koo, K. Jung, J. C. Koo, J.-D. Nam, Y. K. Lee, and H. R. Choi, "Development of soft-actuator-based wearable tactile display," *IEEE Trans. Robot.*, vol. 24, no. 3, pp. 549–558, Jun. 2008.

[7] G. Burdea, J. Zhuang, E. Roskos, D. Silver, and N. Langrana, "A portable dextrous master with force feedback," *Presence, Teleoperators Virtual Environments*, vol. 1, no. 1, pp. 18–28, 1992.

[8] R. E. Fan, M. O. Culjat, C.-H. King, M. L. Franco, R. Boryk, J. W. Bisley, E. Dutson, and W. S. Grundfest, "A haptic feedback system for lower-limb prostheses," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 16, no. 3, pp. 270–277, Jun. 2008.

[9] C. P. Premarathna, D. S. Chathuranga, and T. D. Lalitharatne, "Fabrication of a soft tactile display based on pneumatic balloon actuators and voice coils: Evaluation of force and vibration sensations," in *Proc. IEEE/SICE Int. Symp. System Integr. (SII)*, Dec. 2017, pp. 763–768.

[10] M. W. Uddin, X. Zhang, and D. Wang, "A pneumatic-driven haptic glove with force and tactile feedback," in *Proc. Int. Conf. Virtual Reality Visualizat. (ICVRV)*, Sep. 2016, pp. 304–311.

[11] J. J. Huaroto, E. Suarez, H. I. Krebs, P. D. Marasco, and E. A. Vela, "A soft pneumatic actuator as a haptic wearable device for upper limb amputees: Toward a soft robotic liner," *IEEE Robot. Autom. Lett.*, vol. 4, no. 1, pp. 17–24, Jan. 2019.

[12] Smooth-On. *Ecoflex 00-30*. Accessed: Dec. 14, 2019. [Online]. Available: https://www.smooth-on.com/category/platinum-silicone/

[13] A. Talhan and S. Jeon, "Prostate tumor palpation simulator based on pneumatic and augmented haptics," in *Proc. Int. AsiaHaptics Conf.* Singapore: Springer, 2016, pp. 353–357.

[14] A. Talhan and S. Jeon, "Programmable prostate palpation simulator using property-changing pneumatic bladder," *Comput. Biol. Med.*, vol. 96, pp. 166–177, May 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0010482518300611

[15] Sooth-on. *Curing process*. [Online]. Available: https://www.smooth-on.com/products/ecoflex-00-30/

[16] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, "Soft robotic glove for combined assistance and at-home rehabilitation," *Robot. Auto. Syst.*, vol. 73, pp. 135–143, Nov. 2015.

[17] A. Picu, "Study about evaluation of human exposure to hand-transmitted vibration," *J. Sci. Arts*, vol. 2, no. 4, pp. 355–360, Dec. 2010.

[18] S. Aatola, M. Färkkilä, I. Pyykkö, O. Korhonen, and J. Starck, "Measuring method for vibration perception threshold of fingers and its application to vibration exposed workers," *Int. Archives Occupational Environ. Health*, vol. 62, no. 3, pp. 239–242, 1990.

[19] Takescan. *Datasheet A201 Flexiforce Sensor*. [Online]. Available: https://www.tekscan.com/resources/product/flexiforce-a201-datasheet

[20] Tekscan. *Sensors*. [Online]. Available: https://www.tekscan.com/support/faqs/how-do-i-calibrate-my-flexiforce-sensor

[21] R. Balasubramanian and V. J. Santos, *The Human Hand as an Inspiration for Robot Hand Development*, vol. 95. Cham, Switzerland: Springer, 2014.

[22] Hydraulics and pneumatics. *Importance of Hose*. [Online]. Available: https://www.hydraulicspneumatics.com/other-technologies/chapter-3-pipe-tube-and-hose

[23] R. W. Colbrunn, G. M. Nelson, and R. D. Quinn, "Modeling of braided pneumatic actuators for robotic control," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, vol. 4, Oct./Nov. 2001, pp. 1964–1970.

[24] S. Exner, "Experimentelle untersuchung der einfachsten psychischen processe," *Archiv für die gesamte Physiologie des Menschen und der Tiere*, vol. 7, no. 1, pp. 601–660, Dec. 1873, doi: 10.1007/BF01613351.

[25] S. Exner, "Experimentelle untersuchung der einfachsten psychischen processe," *Pflügers Archiv Eur. J. Physiol.*, vol. 11, no. 1, pp. 403–432, 1875.

[26] I. M. Vogels, "Detection of temporal delays in visual-haptic interfaces," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 46, no. 1, pp. 118–134, 2004.

[27] T. Kaaresoja, S. Brewster, and V. Lantz, "Towards the temporally perfect virtual button: Touch-feedback simultaneity and perceived quality in mobile touchscreen press interactions," *ACM Trans. Appl. Perception*, vol. 11, no. 2, Jun. 2014, Art. no. 9, doi: 10.1145/2611387.

[28] A. Talhan, H. Kim, and S. Jeon, "Wearable soft pneumatic ring with multi-mode controlling for rich haptic effects," in *Proc. ACM SIGGRAPH Posters*, New York, NY, USA, 2019, Art. no. 65, doi: 10.1145/3306214.3338613.

AISHWARI TALHAN received the B.E. degree in information technology and the M.E. degree in embedded systems and computing from Nagpur University, India, in 2005 and 2009, respectively, and the Ph.D. degree in computer engineering from Kyung Hee University, South Korea, in August 2018. She was a Lecturer with Nagpur University and a Software Developer with Nagravision (formerly EnMedia Technologies), Bengaluru, India. She is currently working as a Postdoctoral Research Fellow with Kyung Hee University. Her research focuses on haptics, soft haptics, actuators, augmented reality, simulator, medical applications, and virtual reality environments for various applications.

HWANGIL KIM received the B.S. degree in computer science and engineering from Kyung Hee University, South Korea, in 2018, where he is currently pursuing the M.Sc. degree with the Department of Computer Science and Engineering. His research focuses on haptic rendering, simulation in virtual reality environment and human–computer interaction.

SEOKHEE JEON received the B.S. and Ph.D. degrees in computer science and engineering from the Pohang University of Science and Technology (POSTECH), in 2003 and 2010, respectively. He was a Postdoctoral Research Associate with the Computer Vision Laboratory, ETH Zurich. In 2012, he joined the Department of Computer Engineering, Kyung Hee University, where he is currently an Associate Professor. His research focuses on data-driven haptic modeling and simulation, haptic-enabled augmented reality systems, and applications of haptics technology to medical training.