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Development of human-touch smart armband for tele-haptic communication using a fabric-based soft pneumatic actuator

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Abstract

This study aimed to develop a human-touch smart armband that can transport emotional tactile stimuli to individuals in distant places. To simulate human touch stimuli, a soft pneumatic actuator (SPA) which we refer to in this study as "SPA touch," of size 7 cm × 7 cm and thickness 0.3 cm was designed using fabric and silicone with nine touch points, which can be individually inflated and allocated within the actuator. The use of thermoplastic polyurethane-coated fabric as a backing material helps obtain one-side inflation toward the skin effectively. By controlling the position and duration time of the inflation of the nine touch points, three basic touch modes ("Touch," "Double touch," and "Drag") and three emotional tactile gestures ("Patting," "Hugging," and "Caressing") were programmed using Python. The evaluation of the operating performance of the basic touch modes and emotional tactile gestures showed that "SPA touch" could properly create and transmit touch stimulation remotely. The human-touch smart armband developed in the process of this study can be used for novel tele-haptic communication with individuals in distant places, such as nursing homes.

Keywords: Tele-haptic, Human-touch, Wearable, Soft pneumatic actuator, Emotional tactile gesture

Introduction

In the era of rapid digital transformation, the COVID-19 pandemic has accelerated and popularized online non-face-to-face communication. Accordingly, well-functioning social practices, such as human face-to-face communication and old age care, have been disrupted (Allwood, 2017). However, digitalization has led to increased efficiency, greater speed, and lower costs in many fields. Nevertheless, although most non-face-to-face communication can happen digitally, technology cannot replace emotional communication. Therefore, the need for "human touch" technology is increasing. "Human touch" is defined as "a friendly and pleasant way of treating other people that makes them feel relaxed" (Cambridge Dictionary, 2023). Nowadays, the significant aspects of human touch namely human temperature and emotion can be conveyed through technology. It is accomplished by understanding the feelings, emotions, and interactions of the users, which compensate for the lack of emotional communication.

While online communication mainly relies on sight and sound, touch has been confirmed as a vital means of communication (Finnegan, 2020; Ozioko et al., 2020; Riddle & Chapman, 2012).

Reportedly, as video services lack non-verbal expressions, they are deficient in understanding the feelings and emotions of others (Farooq et al., 2021). App et al. (2011) reported that different emotions are effectively transmitted through nonverbal communication channels such as body, face, and touch that support intimate emotions. The authors also claimed that devices that utilize tactile sensations are used for therapeutic purposes as well. Elderly people, especially those suffering from dementia, need to interact smoothly with caregivers because of the cognitive, social, and emotional decline and because touch-based interactions help improve relationships (Douglas, 2021; Sumioka et al., 2021).

Haptic technology physically implements and transmits the sense of perception using all tactile organs of the human body. Tele-haptics is a technology that remotely reproduces tactile sensations through human–computer interactions (Shen et al., 2004), enabling communication of tactile sensations in different spaces and remote situations. One of the most actively used areas of tele-haptic technology is extended reality (XR). XR can be applied to various fields, such as education, healthcare, shopping, manufacturing, and gaming, as well as to rapidly expanding non-face-to-face services, because it provides new experiences beyond the constraints of reality (Kim & Choo, 2021; Park et al., 2018).

Tactile expression devices, which convey texture, pressure, vibration, or pain through mechanoreceptors in contact with the skin, require actuators to implement haptic feedback such as vibration or movement.

MEM-driven actuators, which are mostly used in robotics and mechatronics, can provide accurate motion control but have limited flexibility for realistic tactile expression and are constrained by size, weight, and noise when it comes to wearable applications (Shull & Damian, 2015). In contrast, pneumatic actuators use air and water to deliver tactile sensations over an entire low-pressure area.

Pneumatic actuators are mainly rubberized, and the McKibben and Warsaw types are used as artificial muscles that generate force by contracting and expanding using elasticity and regulating the internal pressure of a rubberized tube. Pouch-type actuators generate force using the mechanical action of air, water, and fluid (Robertson et al., 2017). However, pneumatic actuators are mainly used in robots and cannot provide information on the surface shape of real objects. Furthermore, operational issues related to the weight and portability of the equipment still exist.

Thus, a soft actuator can be an alternative. Soft actuators can be created with soft materials such as silicone to ensure good conditions for use in wearable devices that require flexibility and light fit.

Wearable haptic devices in the form of clothing, such as gloves and vests, aimed at transmitting a realistic sense of touch are the recent trend, and they allow direct contact with the human body. Therefore, the need for active feedback, portability, strong tensile strength, and good contractility has been emphasized in soft actuators. A soft pneumatic actuator (SPA) is a popular choice in many recent soft robot applications owing to its high customizability, lightweight, and inherent safety for various human interaction applications. Silicone-based pneumatic actuators are used in medical, rescue, and finger robots and for rehabilitation treatments.

In a study on haptic feedback using SPAs, Suh et al. (2014) developed “SPA skin” that can be applied to a vibro-tactile feedback system for wrist rebalancing using silicone. Liu et al. (2021) developed an SPA that can simultaneously deliver tactile and thermal sensations using a PVC pouch and fluid (“ThermoCares”). Khin et al. (2016) developed haptic actuators of different shapes and sizes by attaching polyurethane to polyester fabric through ironing. They measured the magnitude of the force according to the air pressure and found that a force of approximately 2.20 ($\pm$0.017) N was generated when 80 kPa was supplied. Delazio et al. (2018) developed a “Force Jacket” equipped with a polyurethane pouch-type airbag and force sensors that provide precisely directed force and high-frequency vibrations. They simulated the pressure and vibration-based feel effects such as those of a punch, hug, and snake moving across the body by controlling the pneumatically-actuated airbags. Zhu et al. (2020) introduced a fabric-based forearm-wearing “PneuSleve” that can provide a wide range of tactile stimuli including compression, skin stretching, and vibration. These studies have shown that the SPA is a suitable tool for creating tactile stimuli that can simulate human touch.

Therefore, recognizing the need for remote emotional communication, in this study we designed a smart armband that can deliver touch stimuli over a long distance, using a SPA which is known to be suitable for generating human skin touch stimuli, and reported its performance.

The following steps were followed to this end.

1. The SPA was devised using silicone and fabric capable of soft-touch implementation (SPA touch). Its performance was evaluated through the measurement of minimum driving voltage and expansion cycle required for touch detection.
2. Three basic touch modes (“Touch”, “Double touch”, and “Drag”) and three emotional touch modes (“Patting”, “Hugging”, and “Caressing”) were designed and programmed to implement tactile sensitivity through “SPA touch.”
3. Using “SPA touch” and programmed emotional touch gestures, a human-touch smart armband was assembled.
4. The performance of the smart armband was tested using subject testing for the three basic touch modes and the three emotional tactile gestures.

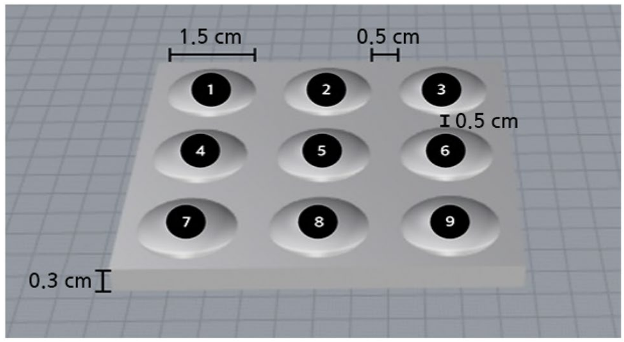
Methods

Design of “SPA touch”

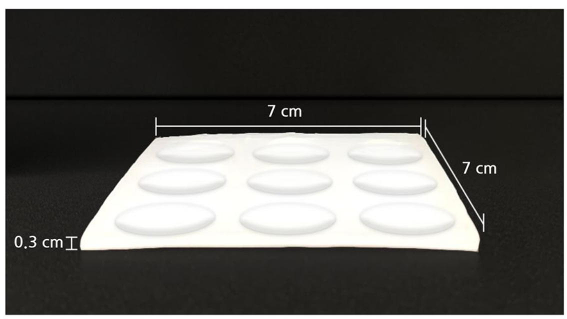
The human-touch armband devised in this study was designed to transmit touch sensitivity by programming nine individual touch points that simulate the touch of a finger and palm to inflate/deflate according to time and position. Therefore, an actuator capable of simulating touch stimulation of a finger and palm had to be designed. Thus, an air pump-driven pneumatic actuator “SPA touch” was designed using silicone and fabric. The shape of the actuator was chosen to be square shape of size of 7 cm $\times$ 7 cm and thickness 0.3 cm to achieve an emotional tactile gesture in the upper finger of the hand (Mun et al., 2018; Yu et al., 2019). To obtain one-way expansion, three-layer

Table 1 Characteristics of Dragon Skin™10 medium

High-half viscosity (Pa s)	Tensile strength (Pa)	Shore A	Curing time (s)
23	3.28×10^6	10	1.8010×10^4



(a)



(b)

Fig. 1 **a** Three-dimensional virtual image of designed "SPA touch" and **b** "SPA touch" made of silicone and a non-stretchable fabric with nine touch points for one side inflation

construction was adopted (Suh et al., 2014). For the skin contact side, a stretchable layer, which was inflated by the air, was made of low-viscosity silicone (Dragon Skin™ 10 medium, Table 1) to create touch patterns. For the backing layer, a non-stretchable thermoplastic polyurethane (TPU)-coated lightweight polyester fabric (PET 88%, TPU 12%) was used. If both layers are made of silicone, expansion can occur in both directions when air is injected. Therefore, the non-stretchable material is placed on the side that does not require expansion to induce effective inflation in one direction. The "SPA touch" consisted of nine round touch points, 1.5 cm in diameter, 0.3 cm in height, and 0.5 cm apart from each other (Conradi et al., 2015). The nine touch points were created by placing a circular cut PVC fabric (mask layer) of diameter 1.5 cm between the silicone and TPU fabric layers (Fig. 1a). The PVC fabric allows space for air between the silicone and TPU fabric such that the nine touch points can expand when air is injected into the actuator. Each touch point was connected to an air supply tube (0.2 mm inner diameter) (Fig. 2). The complete "SPA touch" is shown in (Fig. 1b).

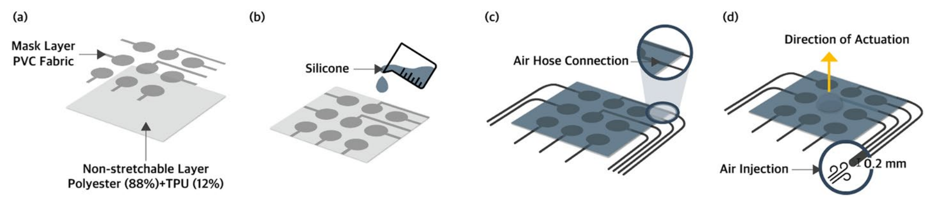


Fig. 2 Fabrication process of "SPA touch": **a** mask layers (PVC fabric) are attached to the non-stretchable fabric layer (TPU-coated polyester); **b** silicone is poured over the mask layer and fused with the fabric layer; **c** an air hose is placed for each area; **d** air is injected through the tubes and the inflation takes place on one side

Pneumatic generator system configuration

The pneumatic generator for injecting air into the actuator according to the touch pattern was manufactured using an Arduino (Mega 250), which is compatible with a solenoid valve and an air-pump pneumatic actuator device. The emotional tactile gestures were implemented by injecting air into the pressure devices using a vacuum compressor that generates air using a reliably driven air pump. The characteristics of the vacuum compressor were: rated DC voltage of 6 V, rated current of 400 mA, pressure of 100 kPa, negative pressure of −60 kPa, flow rate of 3.2 L/min, and weight of approximately 62 g.

Nine mini solenoids (rated voltage 5 V DC, rated current 300 mA, output 1.7 W) were operated using a relay module (rated voltage 5 V DC) to control nine independent air injections in total. The location of the inflation area of "SPA touch" corresponding to the setting mode was coded using the Arduino program and connected to the Python program, and "SPA touch" was controlled using the Python program (Fig. 3).

Identifying the required performance of the pneumatic generator system

To measure the minimum driving voltage and air injection pressure required for touch sensing, a force sensing resistor (FSR) sensor was used. The FSR was attached to an acrylic panel (169.50 g) fixed at a distance of 0.7 cm from the floor, and the reading of the sensor was confirmed to be zero (Fig. 4). For the inflation test of the touch points of "SPA touch," the FSR resistance value was measured for 1000 ms by operating a motor of 100 hPa of hydraulic pressure at 5 V, 6 V, and 7 V voltages.

Setting of basic touch modes and emotional tactile gestures

To implement human-touch communication using the nine touch points in "SPA touch," inflation patterns were designed. "Touch," "Double touch," and "Drag" were set as the three basic touch modes (Villamor et al., 2010). To convey emotions through emotional tactile gestures, three modes were selected: "Patting," "Hugging," and "Caressing," which are commonly used touch gestures to convey positive emotions (Hertenstein et al., 2009). Figure 5 displays the definition of the inflation pattern of the three basic touch modes and three emotional tactile gestures. "Touch" stimulation was set as air injection once for 500 ms of inflation time at the 5th touch point, whereas the stimulation of "Double touch" was set as twice that the "Touch" with an interval of 500 ms. "Drag" was defined in such a way that the 4th, 5th, and 6th positions of "SPA touch" were sequentially expanded for 500 ms in 500 ms intervals. A combination of these three basic touch modes can be used to design various touch signals as needed. The emotional tactile gesture of "Patting" was designed to be similar to a heartbeat, and it was defined to inflate three times simultaneously in all positions for 1000 ms in intervals of 1000 ms. "Hugging" was defined by maintaining 3000 ms of expansion and 3000 ms of duration in all positions to express the feeling of hugging an arm. Finally, "Caressing" was designed to express the feeling of stroking the arm. In the order of column 1 (1, 4, 7), column 2 (2, 5, 8), and column 3 (3, 6, 9), the touch point in each column expands in "Drag" mode with an inflation time of 20 ms and interval of 20 ms. It was designed to repeat the entire process twice (Fig. 5, Table 2).

Armband fabrication using "SPA touch"

Using the developed "SPA touch," an armband that can be worn on the forearm was constructed. The location of the touch stimulus was selected at the front of the forearm, which showed a high degree of reaction according to the results of the pneumatic recognition experiment on each arm (Delazio et al., 2018). The skin side of "SPA touch," made of silicone, was covered with thin highly-stretchable nylon fabric to improve comfort during contact and protect the silicone surface from abrasion and dirt. A polyester fabric was wrapped around the outermost layer (Fig. 6). Hook and loop fasteners were used to secure the armband on the arm of the wearer.

Wear trial for performance test of the human-touch smart armband

A total of 10 subjects (five males and five females) in the age group of 20–30 years participated in the test (IRB number: KHSIRB-21-494 (RA)). The participation was limited to individuals without sensory abnormalities in the left arm. The experiment was conducted in a climate-controlled chamber at 23 °C and 65% RH for seven days between November 15 and 21, 2021. The participants were required to wear an eye mask, ear plugs, and a headset that emitted white noise to focus on the tactile sensation.

The participants wore the human-touch smart armband on their left arm, and the operation settings of the three basic and three emotional touch modes (Table 2) were explained to them. Subsequently, each touch mode was given to the participants three times for 1 min, and after the three repeated stimuli, the participants were asked to answer to which touch mode the given stimulus belonged. The correct answer rate was calculated based on the results for each touch mode.

Results and Discussion

Configuration of "SPA touch"

"SPA touch" is a fabric-based silicone actuator that consists of nine individually-controlled touch points. When silicone is poured on the 7 cm-wide TPU-coated polyester fabric, the nine round PVC fabrics of diameter 1.5 cm placed on the fabric layer prevent the adhesion of the fabric to the silicone.

These non-adhesive areas created nine switch-type touch points in the actuator. When air was injected into the completed "SPA touch," the polyester fabric coated with TPU acted as a film, and air flowed through one direction of the silicone side. After air was injected at 100 hPa for 500 ms, it was confirmed that the actuator expanded to a

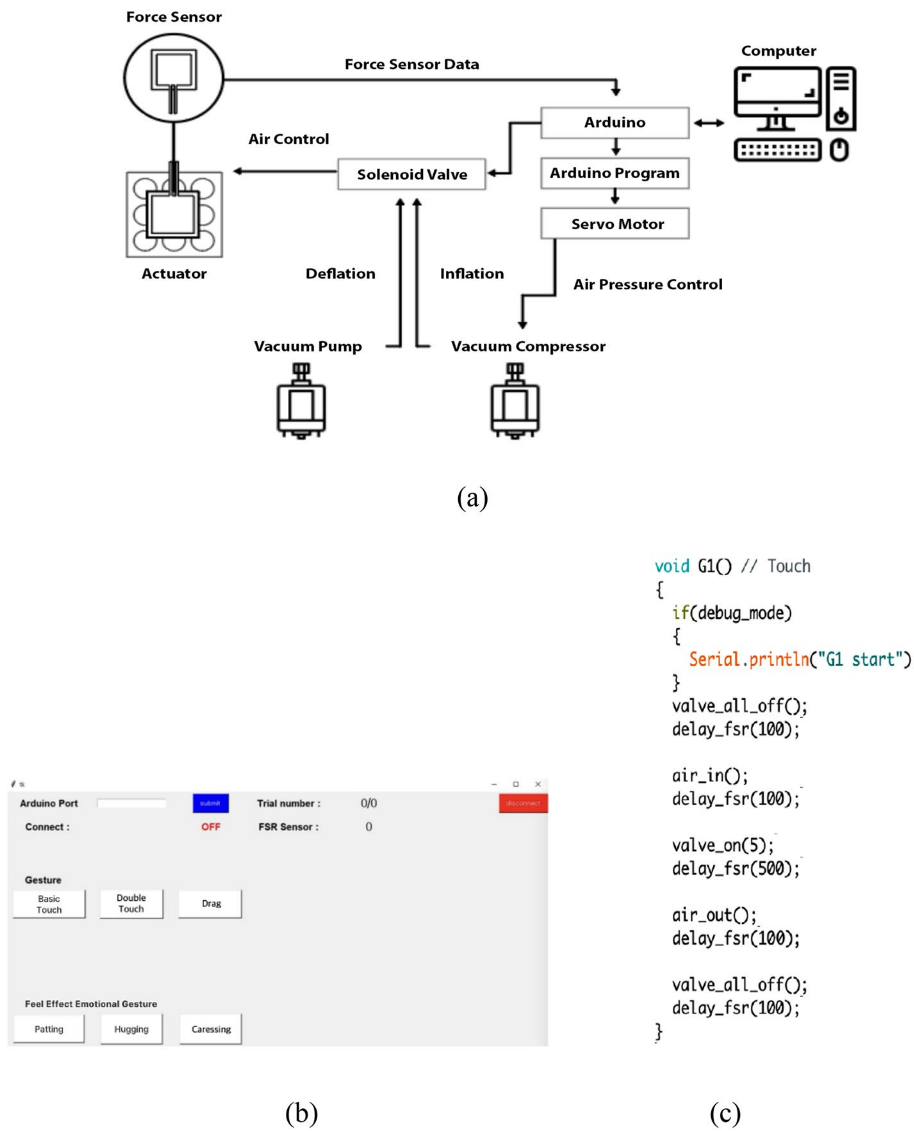


Fig. 3 **a** System configuration of "SPA touch" **b** GUI configuration of Python program, and **c** Arduino coding of basic touch mode "Touch"

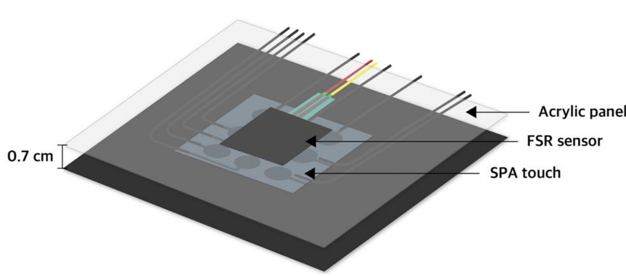


Fig. 4 Setting for evaluating "SPA touch" inflation performance

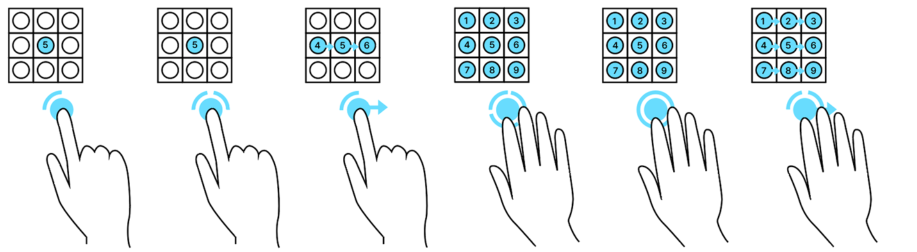


Fig. 5 Definition of basic ("Touch", "Double touch", and "Drag") and emotional touch ("Patting", "Hugging", and "Caressing") gestures

Table 2 Operation setting of basic and emotional touch modes

Gesture		Location of touch point	Parameters	Setting(ms)
Basic touch	Touch	5	Inflation time	500
	Double touch	5	Inflation time	500
			Interval	500
			Repeat	2
	Drag	4 → 5 → 6	Inflation time	500
			Interval	500
Emotional touch	Patting	all (1–9)	Inflation time	1000
			Interval	1000
			Repeat	3
	Hugging	All (1–9)	Inflation time	3000
			Duration	3000
	Caressing	1 → 4 → 7	Inflation time	20
		2 → 5 → 8	Interval	20
		3 → 6 → 9	Repeat	2

height of 0.7 cm. The total thickness of the fabric-based pneumatic actuator developed in this study (SPA touch) was 0.3 cm. Because "SPA touch" is fabric based and satisfies the safety and flexibility requirements of the material, it is suitable for use as a wearable device because it has more durability than silicone-only materials.

Operation performance of "SPA touch"

To determine the appropriate amount of air to inflate the touch point, the resistance value of the FSR was measured at 5 V, 6 V, and 7 V for 1000 ms by driving the motor (100 hPa) connected to the "SPA touch." The measurement was taken five times at each voltage, and the average values are shown in Fig. 7. At 5 V, the touch point was not sufficiently inflated, and the initiation was delayed by 200 ms because of insufficient air. At 7 V, the touch point started to be inflated, but a delay time of 200 ms was observed for the escaping air. Because the touch implemented in this study includes repeated operations of inflation and deflation, if the deflation is delayed while the injection is stopped, it conflicts with the next injection, and the touch pattern is not properly implemented. Further, at 7 V, the touch point expanded to the maximum, resulting in an excessively

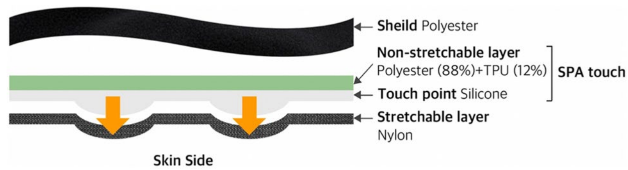


Fig. 6 Layer configuration of human-touch smart armband

hard touch, which was considered unsuitable because it could be irritating when "SPA touch" was worn in close contact with the skin in the armband. However, at 6 V, no issues were observed in implementing the touch pattern with a short delay of approximately 100 ms when the injection started, and an immediate deflation was observed when the injection was stopped. Therefore, 6 V was selected for the operation. Figure 8 shows the inflation profile at touch point 5 of "SPA touch" when the human-touch smart armband is operated at 6 V.

Implementation of basic and emotional touch modes of "SPA touch"

To confirm the implementation of the programmed basic touch modes and three emotional tactile gestures, the FSR resistance value was measured at the required locations of touch points for each mode by operating a motor with a hydraulic pressure of 100 hPa at 6 V.

Since basic emotional touch gestures include repeated inflation with intervals, single touch and two, three, and four consecutive touches were tested for 500 ms of injection with 20 ms intervals (Fig. 9). The inflation time (500 ms) corresponds to the operation setting of "Touch" and "Double touch," and the interval time (20 ms) corresponds to the "Caressing" operation setting, as shown in Table 2.

Consequently, the single touch showed a 100 ms delay, and the inflation was maintained for 500 ms (Fig. 9a). In the continuous touch, the delay time was longer than that of the single touch because air was expelled in a short interval of 20 ms, after which air was injected again. However, it was confirmed that the peak patterns were consistent, the peak remained stable, and the boundary between deflation and inflation appeared clearly. Thus, "SPA touch" could appropriately implement touch stimuli through the program (Fig. 9b–d). In regard to the emotional tactile gestures, it was confirmed that "Patting" worked suitably with regular inflation of 1000 ms at intervals of 900–1000 ms. The "Hugging" gesture was confirmed to have a static pressure ratio for 3100 ms and was suitable operated for a duration of 3000 ms. The FSR resistance value of "Caressing" was measured for 700–800 ms per cycle and was repeated twice in the first (1,4, and 7), second (2,5, and 8), and third columns (3,6, and 9). Emotional tactile gestures showed a lower resistance value than the basic touch modes, which could be attributed to the increased number of operating touch points (Fig. 10).

Performance verification of the human-touch smart armband worn by subject

A wear test was conducted to ensure that the touch stimuli generated by the Human Touch armband were accurately detected by the wearer. The results showed that "Touch" and "Double touch" in the basic touch modes were recognized with 100% correct

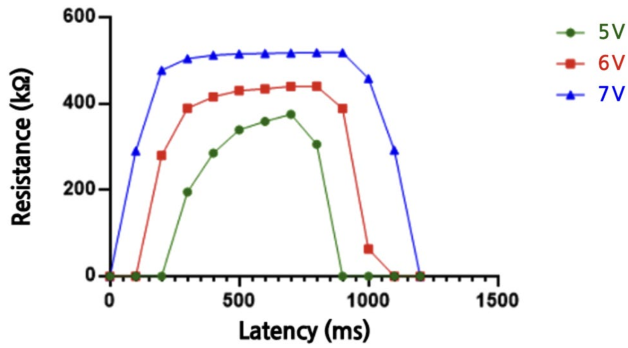


Fig. 7 Average FSR resistance value according to the V value

Fig. 8 Before (**a**) and after (**b**) inflation at touch point 5 (100 hPa)

response rate, while "Drag" was correctly recognized by 60%. In the emotional touch modes, "Hugging" showed a 100% correct response rate and "Patting" and "Caressing" showed 70% correct answer rate, respectively.

There was no statistically significant difference in the percentage of correct answers between males and females, but it was found that one male and one female confused "Caressing" with "Patting". In addition, 20% of the participants confused "Patting" with "Drag" and they were all female, while 20% confused "Caressing" with "Drag" and they were all male. Therefore, "Drag" had a relatively low percentage of correct answers at 60% for both men and women (Table 3).

In both the basic touch mode and the emotional touch mode, single-shot stimuli can be recognized with 100% accuracy, and the correct recognition rate is somewhat lowered in the case of stimuli that require continuous expansion of touch points.

Among them, most of the confusion was between "Drag" in basic touch mode and "Caressing" and "Patting" in emotional touch mode, so if only the emotional touch modes are presented, it can be thought that remote emotional communication such as "Hugging", "Patting" and "Caressing" can be effectively achieved.

Conclusions

While digitization has brought the benefits of increased efficiency and reduced costs in many areas, it has also caused negative effects on human face-to-face communication and emotional affinity. Therefore, this study devised a human-touch smart armband for tele-haptic communication to help convey tactile emotional gestures to individuals at distant locations. To simulate human-touch gestures using fingers and palms, a fabric-based SPA was designed and named "SPA touch"—a thin and flexible pneumatic actuator designed with fabric and silicone with nine individually inflatable

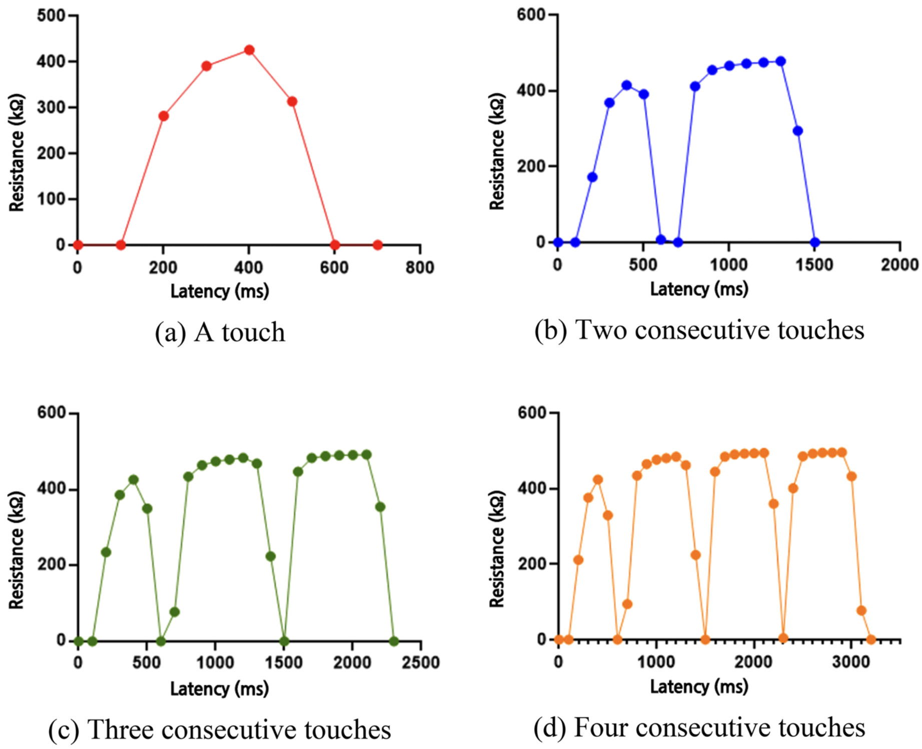


Fig. 9 FSR resistance value of the touch cycles for 500 ms inflation with 20 ms intervals at touch point 5 (average value of three repeated measurements) **a** A touch; **b** two consecutive touches; **c** three consecutive touches; **d** four consecutive touches

touch points. It has a two-layer structure with a silicone layer joined on top of the base fabric layer, and inflatable touch points were created by placing round PVC fabric of diameter 1.5 cm between the silicone and base fabric layers to secure air spaces at each position. Using non-stretchable TPU-coated fabric as the base fabric, the touch points were inflated only in the direction of the silicone layer by injecting air, which generated a sufficient volume of touch stimuli on the skin. The pattern of inflation/deflation of the nine touch points was programmed to implement three basic touches ("Touch", "Double touch", and "Drag") and three emotional tactile gestures ("Patting", "Hugging", and "Caressing"). A combination of the three basic touches can be used to create various touch languages. The emotional tactile gestures were designed to simulate the feelings of patting, being embraced, and gentle stroking.

The operating performance of "SPA touch" was evaluated using an FSR. It was verified to have a constant inflow and suction of air at each gesture mode, and it could consistently generate tactile stimuli defined as basic and emotional touch gestures.

The human-touch smart armband was manufactured by placing the developed "SPA touch" such that it would be on the outer skin surface of the forearm. The silicone touch points of "SPA touch" were covered with thin, elastic nylon fabric to secure durability while delivering tactile stimulation without barriers. Hooks and loops were used as fasteners to easily attach and detach the armband and adjust it to fit the size of the wearer. Through the wear trial experiment, it was confirmed that the basic touch

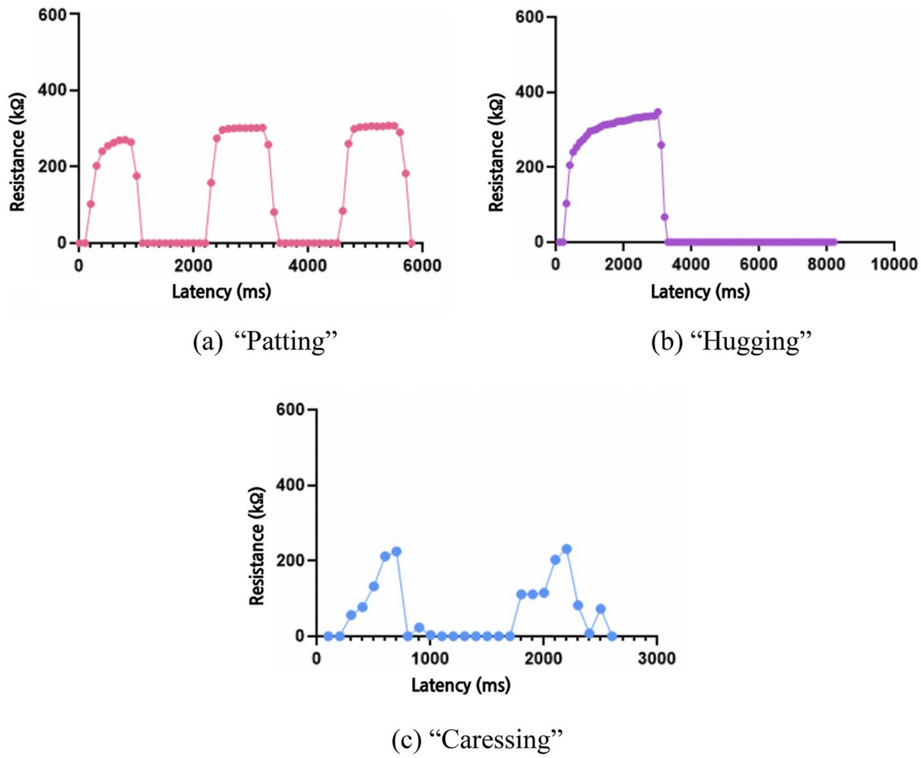


Fig. 10 FSR resistance value of emotional touch modes (average value of three repeated measurements)

Table 3 Correct answer rate of recognition for basic and emotional touch modes

	Touch	Double touch	Drag	Patting	Hugging	Caressing
Total	100%	100%	60%	70%	100%	70%
Female	100%	100%	60%	80%	100%	60%
Male	100%	100%	60%	60%	100%	80%
T-test	P = 1.000	P = 1.000	p = .664	p = .760	P = 1.000	p = .817

and emotional touch modes generated by the human touch smart armband could be properly transmitted to the wearer.

The significance of this study is that a smart armband that can transmit tactile stimulation and emotion over a long-distance using SPA was produced, a pattern that simulated basic touch stimuli and emotional transmission touch modes was devised, and finally, the operation performance of the human-touch smart armband was confirmed through experiments where the device was worn by the participants. The human-touch smart armband developed in this study can be used in nursing homes, for elderly people living alone, and for people living away from sources of emotional comfort. As a future course of action, the end use usefulness of the human-touch smart armband should be verified. The authors have undertaken research in this area, and a report is underway.

Abbreviations

MEM	Micro-electromechanical
PVC	Polyvinyl chloride
FSR	Force sensitive resistor
SPA	Soft pneumatic actuator
TPU	Thermoplastic polyurethane

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Authors' contributions
HC conceived the idea, conducted experiments, collected data, interpreted results, and wrote manuscripts. SY was responsible for the continuous support and supervision of experimental design, experimental results, and manuscript preparation to successfully carry out the research. All the authors read and approved the final manuscript.

Authors' information
HC received her M.A. in Clothing and Textiles from Kyung Hee University. HC studied at the Haptic Engineering Lab in the Department of Information and Telecommunication Engineering at Incheon National University. Her research interest focuses on haptic study using XR, haptic communication and as well as the development of wearable products. SY is a professor in the Department of Clothing and Textiles at Kyung Hee University. SY holds a Ph.D. in Fiber and Polymer Science from North Carolina State University. Her research area includes functional clothing and technical textiles, and she holds several patents on smart clothing and textiles.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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