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# Realizing Physical Multi-haptic Feedbacks using Soft Pneumatic Actuators and Origami Pumps

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## I. Introduction

Recently, soft pneumatic actuators have attracted enormous attention as one of the hpatic techniques applied in wearable devices for rendering the physical senses. The soft pneumatic actuator is typically made of inflatable soft materials and operates by applying positive relative pressure to the inner cavity of the actuator. It is advantageous to configure the actuator in various shapes according to specific applications, as the inflation direction can be controlled by methods of inserting fabric materials or designing its structure. By controlling inflation directions, these actuators can generate high force in a narrow area. In addition, the soft pneumatic techniques are relatively inexpensive and lightweight. Moreover, it is safe for users because there is no electronic device making contact with the skin. However, to provide multiple tactile feedback, including normal force, shear force, and vibration in various directions, several pneumatic actuators have to be integrated into one system.

To allow multiple feedbacks, wearable devices should be also considered at the aspect of wearability. Wearability refers to how comfortable a user feels while wearing a device, without it restricting the movements of their hands. Meanwhile, pneumatic systems typically require external sources of air pressure and valves that are usually bulky and heavy. To overcome the limitations, using an origami technique can be one of solutions. Pumps manufactured using the origami techniques primarily operate through compression via a motor, returning to their original state due to their own elastic resilience. To incorporate these origami pumps into wearable devices, the appropriate size and weight of the pump with the motor should be considered in this system.

Herein, by applying advantages of pneumatic actuators and devising a novel design suitable for fingertips, we propose a Soft Fingertip Pneumatic device (SFP) with an Origami Pump Module (OPM) to provide multiple tactile feedbacks (shear-normal-vibration). Specifically, a unique tactor displacement technique is utilized at the SFP to transmit tactile feedback [1]. As the tactor can freely move, it is capable of delivering normal and shear forces through two pneumatic actuators, a Normal-direction Actuator (NA) and Shear-direction Actuator (SA), as shown in Fig. 1(a). Using this device, we conducted user tests to verify its performance.

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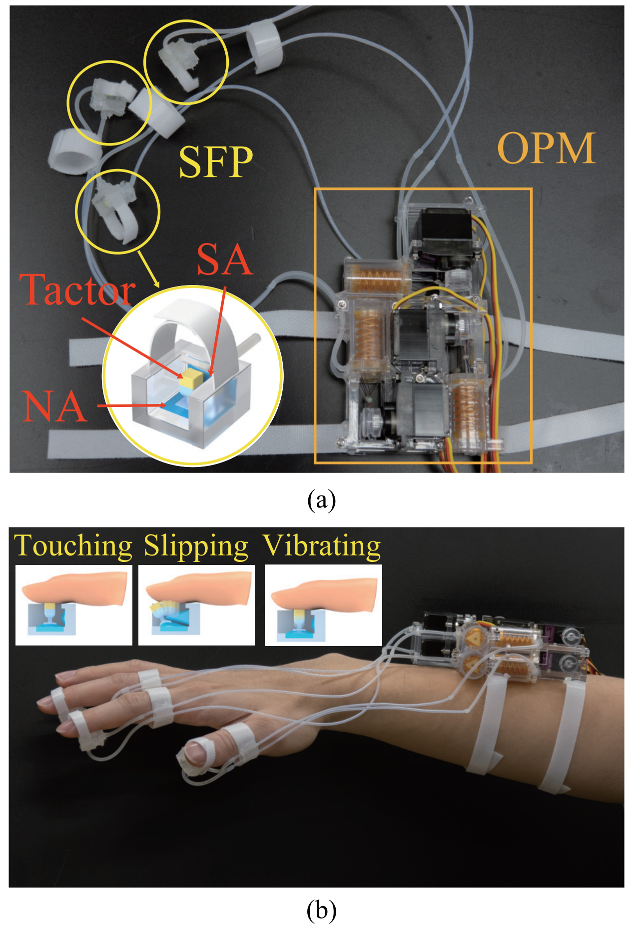


Fig. 1. Phtographs of the SFP and OPMs. (a) Connecting three SFPs and six OPMs. (b) Wearing the device at the finger and forearm. Inserted images showed structures and operation mechanism of the SFP to generate multiple physical haptic feedbacks.

## II. Virtual simulation user test setup

When the two OPMs were connected with two pneumatic actuators, each actuator could operate independently. From these two independent operations, a unique working principle was established to express various tactile feedbacks including touching, slipping, and vibrating, as shown in Fig. 1(b). Specifically, this principle consisted of four stages: (i) the actuators of SFP remain in a stationary state before contacting; (ii) the NA expands to make the tactor reach the fingertip - by activating only the NA, the touch on the fingertip can be maintained continuously to deliver the virtual touching feeling to the user; (iii) the expanding SA shifts the tactor forward - the SA is used to transfer the slipping feeling to the fingertip; and (iv) the SA and NA are contracted, and the SFP returns to its initial state. Moreover, during this process, rapid pneumatic pressure changes can generate vibrating feeling to the fingertip. Combining operations of the NA and SA, three physical haptic feedbacks are generated when a user worn the device, as shown in Fig. 1(b). Furthermore, to provide adequate air pressure, we used two OPMs at each SFP. The origami pumps located in the OPMs were controlled by a servo motor, and generated different air pressure depending on virtual simulations.

To test the proposed device, we conducted a user test with virtual simulation. The device was connected with a virtual reality system to verify its ability to render multiple haptic feedbacks. In this simulations, we focused on slipping and vibrating stimuli through touch. To interact with virtual hands, a virtual hand followed motions of users was designed. We tracked the motions using a hand tracking device (Leap Motion Controller, Leap Motion, Inc., USA). With this virtual hand, six interactions between the virtual reality and our device were simulated, as shown in Fig. 2(a) to (f). These virtual reality simulations consisted of five simulations for shear motions and one simulation for vibration feedback.

Using these virtual simulations, the user test was conducted with 20 participants. The tests was approved by the Korea University Institutional Review Board (Approval Number: KUIRB-2024-0367-01). Twenty Korean participants in their 20s (10 male and 10 female) participated voluntarily in the test with informed consent. All participants were right-handed, and had no restrictions on feeling the touch using their hands. In each test, three situations (no feedback, only normal force existed, and normal-shear forces existed) were tested to assess the performances of the SFP. These performances were scored by seven criteria between realism and artificiality [2].

## III. Result

Fig. 2(g) showed the total user ratings for three situations. The participants felt much more realistic in situations when both normal and shear forces were exerted than in situations when no feedback or only normal force was exerted. Focusing on the normal-shear forces exerted situations at each interactive simulation as shown in Fig. 2(h), we confirmed that the SFP delivered participants a sense of reality as most of the user ratings were between 4 and 5. Specifically, the participants were better able to perceive slippery feelings in Case 3 and 4 simulations with the movement of virtual objects compared to Case 1 and 2 simulations without animation of virtual objects. From this result, we noticed that the SFP could be used more effectively when interacting with moving objects [3], [4]. Moreover, in the case of vibration feedback related to the Case 6 simulation as shown in Fig. 2(i), the SFP could deliver appropriate vibrating stimulus to the user.

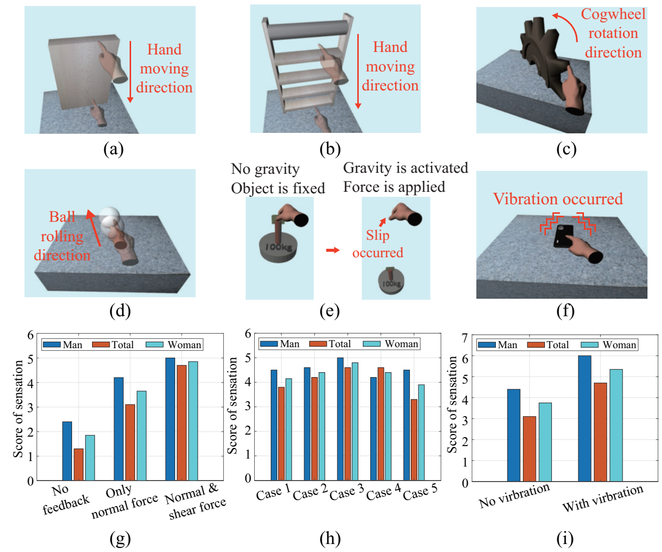


Fig. 2. Demonstration of six rendering tactile feedback interactive simulations and Results of the user test. (a) Case 1: Sweeping down the continuous surface object. (b) Case 2: Sweeping down the discontinuous surface object. (c) Case 3: Touching the finger on the rotating cogwheel. (d) Case 4: Stroking the slippery ball. (e) Case 5: Feeling the sensation of the heavy object falling. (f) Case 6: Touching the vibrated cellphone. (g) Results from the 3 situations: no feedback, only normal force, and normal-shear forces. (h) Results from the 5 interactive simulations related with shear force (Case 1–5). (i) Result from Case 6 for vibration test. The score of 0 to 7 represents a sense of reality and immersion. The score of 0 indicates that there is no sense of reality, and the score of 7 indicates that there is completely a sense of reality.

## IV. Conclusion

In this study, we proposed the Soft Fingertip Pneumatic device with Origami Pump Modules that was able to generate multiple feedbacks through pneumatic pressure. The comfortable and portable design overcame persistent problems with the pneumatic actuator applied at wearable devices (the bulky size and high weight) while still generating enough pneumatic pressure to operate the SFP. In addition, the SFP enabled the generation of normal force, shear force and vibration through only two pneumatic actuators in a narrow area, improving wearability and versatility. User studies showed that the SFP with OPMs enhanced the sense of reality and immersion in virtual environments where users experienced a sense of being swept away.

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