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Design of a Softness Force Feedback Device with Integrated Finger Tactile Sensation

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I. Introduction

As technology progresses, human interaction with virtual environments has become a central focus. To improve the quality and realism of digital experiences, numerous studies have sought to advance Human-Machine Interface (HMI) technologies. Beyond visual and auditory displays, haptic feedback technology has gained significant attention as a crucial element for enhancing user satisfaction. As a result, haptic devices are increasingly being applied in fields such as medical training, professional skill development, and robotics. By delivering both tactile and kinesthetic feedback, the haptic devices replicate the physical properties of objects, enhancing both realism and immersion.

However, many haptic devices focus on a single aspect of force feedback, neglecting the multi-sensory experience required for realistic haptic perception. Some provide only tactile feedback such as skin deformation, but lack kinesthetic feedback such as rigidity or weight. Others offer lateral force to mimic sliding sensation but fail to capture friction. Without integrating both tactile and kinesthetic feedback, the user experience in virtual environments remains incomplete. Research has shown that skin deformation at the fingertips can enhance softness perception, even when kinesthetic feedback is absence. Incorrect tactile feedback can lead to misjudgment when interacting with virtual objects [1].

To address the above-mentioned problems, the study aims to develop a haptic device that integrates both tactile and kinesthetic feedback, enhancing the perception of object softness. The study is expected to improve the realism of virtual experiences.

II. Related Work

Softness feedback devices that reproduce the sensation of softness have been studied by several researchers such as Kimura and Yamamoto [2]. Their system used rigid guide bars on both sides to move a flexible sheet. As the guide bars move, the flexible sheet bends and alters its contact area with the finger, thereby simulating the sensation of envelopment experienced when pressing a soft object.

In addition to mechanical haptic feedback devices, some studies explored the use of electrostatic adhesion. Nakamura and Yamamoto [3] designed a contact plate device consisted of two fan-shaped contact blocks with electrodes attached to them. By controlling the voltage signal, the range of electrostatic adhesion is adjusted, which affects the movement of the contact blocks, resulting in changes in finger envelopment.

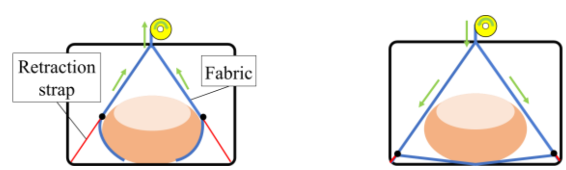
In addition to finger envelopment, some haptic research integrates both tactile and kinesthetic feedback to enhance the perception of softness. For instance, Mete, et al. [4] utilized a ring-shaped soft pneumatic actuator (SPA) and a pouch-motor-driven origami prismatic joint to replicate the softness of objects. The device dynamically adjusts the contact area between the SPA and the fingertip based on the applied finger force, without exerting significant normal force. Meanwhile, the origami prismatic joint, driven by a pouch motor, generates controllable stiffness and displacement. However, their device has limitations in reproducing wide range of stiffness and larger contact area.

III. Method & Approach

When perceiving an object's softness, humans rely on both tactile information from skin envelopment and kinesthetic information from object indentation. Therefore, this study aims to develop a haptic feedback device that can replicate both the sense of wrapping and the stiffness of objects, providing a more realistic and diverse experience of softness sensation.

A. *Wrapping module*

In this study, fabric is used to recreate the sensation of envelopment when an object is being pressed (as shown in Figure 1). By actively controlling fabric movement with a motor, wrapping feedback is applied to the skin of the user's fingertip (Fig. 1 (a)). Compared to simple vibration or static pressure simulation, the use of fabric enables a more realistic replication of the interaction between human fingers and soft materials. Additionally, this approach can adapt to different finger shapes and can dynamically adjust feedback intensity, enhancing immersion and comfort. When simulating the sensation of touching a rigid object, a stretchable retraction strap is used to pull the fabric away, effectively unwrapping it from the user's finger (Figure 1 (b)). A Proportional- Integral-Derivative (PID) controller is used to regulate the fabric's movement that alters the contact area.



(a) wrapping state (b) unwrapping state

Figure 1. Operation principle of wrapping module

B. *Stiffness module*

It is difficult to provide significant feedback force by applying the output torque of the actuators or linkages directly to the users. Our study aims to replicate wide range of object

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softness characteristics. Therefore, the lever principle is used to simulate object stiffness. By adjusting the lever's pivot point, as shown in Fig. 2, the system can provide both low and high softness characteristics. Since this approach does not require the actuator to directly exert force on the users, the output torque demand on the actuator is reduced, also minimizing the risk of user injury.

The proposed system uses a lever mechanism combined with a spring, that has an elastic constant of k and original length of l_s, to generate a pulling force F_s, thus create a feedback force F_f, shown in Fig. 2.

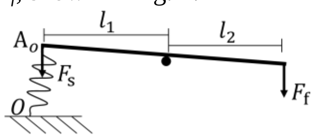

Figure 2. Operation principle of stiffness module.

By analyzing the structure of the mechanism, Eq. (1) is derived to describe the relationship between the device's indentation depth during compression and the resulting feedback force.

$$F_f = (\overline{OA_o} - l_s)k\frac{l_1}{l_2} \qquad (1)$$

The wrapping module proposed in this study differs from previous work [2] in several ways. First, a roller-based retraction mechanism is used to control the movement of the fabric to reduce the spatial requirements of the mechanism. Second, this study incorporates a stiffness module to provide kinesthetic feedback, offering users a more comprehensive force feedback experience.

IV. Preliminary Results & Discussion

Prototypes of the wrapping module and the stiffness module are shown in Fig. 3. For the wrapping module, a roller driven by a DC motor and equipped with an encoder is used to adjust the fabric. Since a visual display will be integrated into the softness feedback device in the future, the device has been designed as a wide platform with two linear rails on both sides, with the stiffness module placed underneath. The linear rail ensures that the platform's movement is perpendicular to the table. Due to the weight of the platform, a constant-force spring (CFS) is implemented to counteract it. An absolute encoder is attached to the rotation axis of the CFS to measure depth as the platform is pressed. In the final setup, the stiffness module is placed underneath the visual display, and the wrapping module is mounted above it, enabling free movement of the wrapping module across the display surface, as shown in Fig. 3.

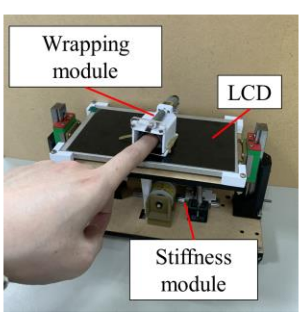

Figure 3. Scenario Illustration.

To accurately control the stiffness of the stiffness module, the stiffness corresponding to different pivot point positions is measured. Based on the measurements, the relationship between the pivot point position and the stiffness is obtained, as shown in Fig. 4.

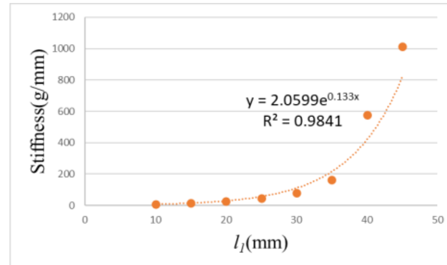

Figure 4. Stiffness at different pivot point.

V. Future Work & Next Steps

Five types of sponges with different stiffness levels will be used to measure changes in the finger contact area when pressed. Experiments on the control of wrapping module will be conducted. By recording the finger envelopment area under different motor rotation angles, regression model between motor rotation angle and coverage area can be obtained. For better user experience, a user interface will be developed.

VI. Conclusion

This study proposes a novel haptic feedback device that integrates both tactile and kinesthetic feedback to enhance the perception of object softness. By combining a fabric-based wrapping module with a lever-based stiffness module, the system effectively simulates the physical properties of different degrees of softness. Preliminary results indicate that this approach can provide a significantly broader range of softness force feedback and a more realistic haptic experience compared to existing single-feedback methods.

Our future work will focus on refining the device's control algorithms, testing more material samples, and conducting user studies to validate the effectiveness of the device in real-world applications. By integrating tactile and kinesthetic feedback, this research contributes to the advancement of human-machine interfaces, with potential applications in virtual reality, medical training, and robotic manipulation.

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