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Compact Four-Degree-of-Freedom Fingertip Feedback Device with Large Range of Motion

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***Abstract*— This work presents a compact, four-degree-of-freedom fingertip cutaneous feedback device capable of rendering normal force, shear, and rotational cues over a large range of motion. Based on a tendon-driven truss mechanism, the device achieved high repeatability in rotational and shear motions, with consistent positional errors that could be addressed through feedforward compensation. A proof-of-concept user study with additional z-axis actuation demonstrated reliable perception of all three tactile cues, achieving accuracies of 98.3% for normal force, 77.5% for rotation, and 91.2% for shear. These results support the feasibility of the proposed mechanism as a compact multi-modal tactile interface for a future handheld haptic device.**

I. INTRODUCTION

Haptic technology enhances task performance and user immersion through tactile feedback. However, compact multi-DoF devices remain challenging, as most fingertip devices provide a limited degree of shear or rotational feedback, often with size and range of motion trade-offs [1]. We present a compact, 4-DoF haptic device that delivers a large range of motion for both shear and rotational feedback by utilizing a truss structure and tendon-driven actuation.

II. WORKING PRINCIPLE

The proposed truss structure (Fig. 1(a)) consists of two identical disc-shaped plates connected by four trusses and a spring. Each plate has sockets for the spherical ends of the trusses. The spring maintains alignment and tendon tension. Both rotational and shear motions can be analytically modeled as functions of the truss tilting angle (Fig. 1(d)). In addition, z-translation can be achieved by lifting the entire lower plate along z-axis for Four tendons are anchored symmetrically in pairs on the upper plate and routed to rear-mounted motors, enabling a compact multi-DoF structure.

Tendon lengths are controlled by motors and computed via inverse kinematics based on the coordinates of anchor points. The computed tendon lengths were then checked using forward kinematics to confirm that they generated the target configuration. The kinematic analysis also provides a workspace visualization of the device motion, as shown in Fig. 1(b). Based on this model, the device is predicted to achieve a range of motion of up to 98° in both directions for rotation and up to 6.79 mm in all directions of the xy-plane for shear motion.

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A prototype of the haptic device is shown in Fig. 1(c). The plates and pulleys were fabricated using a 3D printer (Form 3+, Formlabs) with clear resin, while metal piercings were used as truss members in the proposed mechanism. Servo motors (XC330-M181-T, Robotis) were selected to drive the tendon-based actuation system, a Polyethylene braided line was used for the tendons, and the drive box was made of acrylic. The resulting device is highly compact, measuring 12 mm in diameter and 15 mm in height.

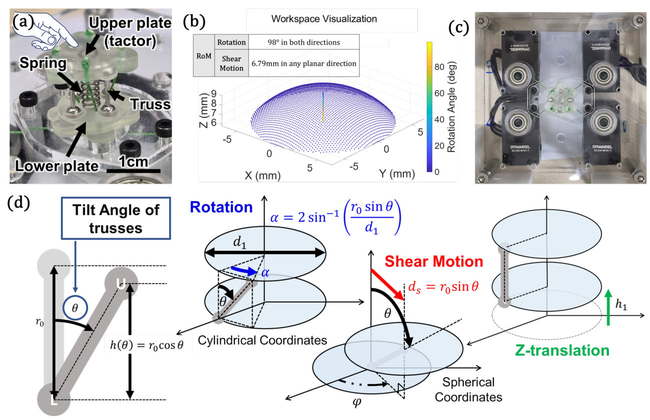

Fig. 1. (a) Truss structure, (b) Workspace visualization, (c) Prototype of the haptic device, (d) Tilt angle θ and induced rotational and shear motion of the upper plate, z-translation

III. CHARACTERIZATION

To evaluate range of motion, repeatability, and positional error, the motion of the upper plate was tracked from a top view using a 4×4 ArUco marker. The experiment included the following motion conditions:

- Rotation: directions (clockwise/counterclockwise) and magnitudes (30°, 60°, and 90°)
- Shear: directions (0°, ±45°, ±90°, ±135°, and 180°) and magnitudes (2, 4, and 6 mm)

Each condition was repeated three times.

The experimental results in Fig. 2(a) and (b) show that the device exhibits low standard deviations (<±0.35° for rotation and <±0.1 mm for shear), confirming the high repeatability of the device. The analysis of the positional error showed that the mean error in the rotational motion was approximately 6.36%, which in practice corresponds to a small angular error of less than 5°. For shear motion, the mean distance error was approximately 6.45%. The mean directional error was 4.66° in the diagonal directions, but decreased to 1.48° in the four principal directions, including high directional accuracy along the principal axes.

IV. PROOF-OF-CONCEPT USER STUDY FOR A 4-DOF HAPTIC DEVICE

The final goal of this work is to realize a four-degree-of-freedom handheld haptic device that can render normal force, rotational, and shear cues while maintaining a constant contact height on the fingertip. This requires an additional mechanism capable of controlling the z-axis position to compensate for height variation and to provide normal force feedback to the fingertip. To explore this possibility before full miniaturization, we constructed a proof-of-concept experimental setup by augmenting the existing mechanism with z-axis actuation. A linear motor was used to generate vertical translation, and a linear guide was introduced to ensure stable linear motion. This setup was intended to verify the operating principle of the 4-DoF concept rather than to represent the final handheld implementation.

In this setup, normal force rendering was indirectly determined by the indentation depth between the tactor and the fingertip. Based on a previously established perceptual model, indentation depths of 2 and 3mm were selected, corresponding to approximately 1.13 and 3.12N.

A total of 10 participants (7 males and 3 females; age range: 23-60 years) took part in the experiment. The study was approved by the Institutional Review Board of Seoul National University (IRB No. 2408/001-021), and informed consent was obtained from all participants prior to the experiment.

The study evaluated the perceptibility of three tactile modalities:

- Normal force: indentation depths of 2 and 3 mm
- Rotation: direction (clockwise/counterclockwise) and magnitude(45° and 90°)
- Shear: direction (0°, 90°, 180°, and 270°) and magnitude (3 and 6mm)

Each condition was presented three times in random order. Participants were asked to identify the presented stimulus according to the corresponding modality.

The results demonstrated that users could reliably distinguish all three tactile cues delivered by the proposed device. In the normal force task, participants achieved 98.3% accuracy, indicating near-perfect discrimination between the two indentation conditions. In the rotation task, the full classification accuracy was 77.5%, while direction accuracy and magnitude accuracy were 80.8% and 93.3%, respectively. This suggests that users were particularly sensitive to rotational amplitude, while directional identification was somewhat more challenging. In the shear task, the full classification accuracy reached 91.2%, with direction accuracy of 99.3% and distance accuracy of 97.5%, demonstrating robust perception of shear cues.

Overall, the user study results provide strong evidence that the proposed truss-based mechanism can successfully render multiple cutaneous feedback modalities. In particular, the high accuracies observed for normal force and shear feedback indicate that the device is well suited for multi-modal fingertip stimulation. The lower, but substantial accuracy for rotation suggests that future improvements in control fidelity and stimulus design may further enhance rotational perceptibility.

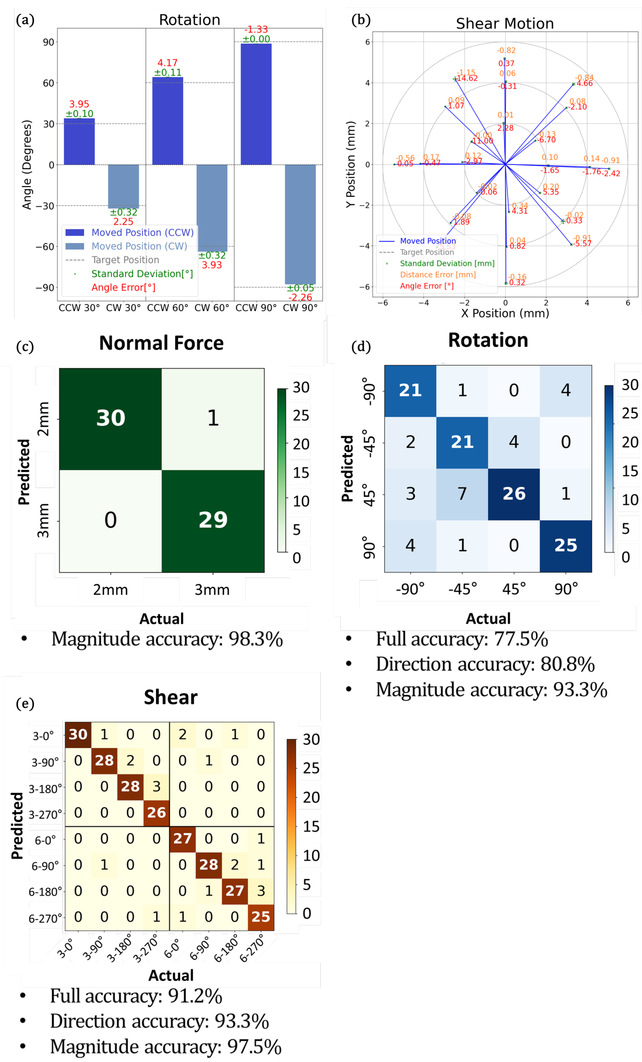

Fig. 2. (a)Rotation analysis, (b)Shear motion analysis, Confusion matrices and accuracies for (c)Normal force (d)Rotation (e)Shear

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