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Design and Fabrication of a Fabric-Based Shear Force Actuator for Enhancing the Continuity of Haptic Perception and Interaction

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I. INTRODUCTION

Haptics, the science and technology of touch-based interaction, plays a critical role in facilitating communication between humans and robots—whether in surgical robotics, prosthetics, or systems that deliver directional cues to users [1], [2]. Both single- and multi-modal haptic devices are being actively researched to enhance the quality of interaction, improve the naturalness of touch, and increase overall user comfort [3], [4], [5].

Many haptic devices primarily use compression-based force displays, where normal forces are applied at discrete points on the skin to simulate contact or texture [3], [5], [6]. Compression feedback remains one of the most accessible and straightforward modalities in haptic interaction, yet it still poses open research questions—particularly regarding how individual users perceive different stimuli at different locations on the body [3], [7]. When implemented as arrays of multiple actuators, compression mechanisms can deliver richer tactile feedback across multiple locations and directions. However, in order to simulate continuous motion, such arrays require fine spatial resolution and rapid actuation to ensure seamless transitions. High-density compression arrays with fast dynamics can approximate smooth surface interactions, but these systems are often mechanically complex and constrained by bandwidth and spatial fidelity. In practice, users may still experience the feedback as a series of discrete points, especially when actuator spacing is limited [4].

In contrast, shear force—defined as lateral force applied parallel to the skin surface—offers a more direct and potentially more efficient method for conveying directional cues and intuitive feedback, as skin stretch and compression are fundamentally different modalities that activate distinct mechanoreceptors in the skin. Shear-based feedback can produce clearer, more intuitive perceptual effects even at lower actuator densities and with slower actuation speeds. Accordingly, a range of shear actuation strategies has been explored, in both single and multi-degree-of-freedom configurations [8], [9], [10], [11]. However, many of these systems remain bulky.

To address these limitations, we developed a fabric-based Z-shaped actuator designed to generate controlled shear forces on the skin (Figure 1) [12]. This study presents the design, fabrication, and initial evaluation of the actuator, with the goal of contributing a lightweight and flexible solution for future wearable haptic interfaces that utilize skin stretch.

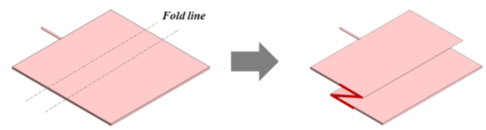

Figure 1. Schematic Illustration of a Z-Shaped Shear Actuator Formed by Folding a Pouch Motor

II. DESIGN AND DEVELOPMENT

We present the design and fabrication of origami-inspired soft fabric pneumatic actuators made from TPU-coated fabrics using heat bonding. Flat actuators provide only normal force, while Z-folded configurations generate shear motion through the unfolding and folding process (Figure 1). Fabrication involves a single-step process for flat actuators and a two-step process for folded ones: bonding the chambers at 150 °C and fixing the folded shape at 100 °C. Different actuator parameters are selected based on their expected influence on force output and displacement (Figure 2 a). By varying these parameters, a range of actuator shapes and stiffnesses can be achieved (Figure 2 b).

III. ANALYSIS

Finite element simulations were performed using ABAQUS to assess the shear force and displacement output of the actuator. The actuator was placed on top of the skin and compressed by a layer of clothing (Figure 2 c). The actuator and clothing were modeled with linear elastic material

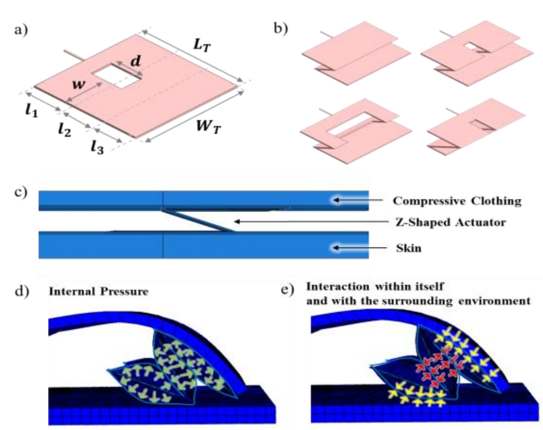

Figure 2. a) Design Parameters of the Z-Shaped Shear Actuator; b) Four Variations of the Z-Shaped Shear Actuator; c) Contact Environment of the Shear Actuator Relative to Anchoring and Skin; d) Internal Pressure Setting of the Shear Actuator; e) Interaction Setting with the Surrounding Environment

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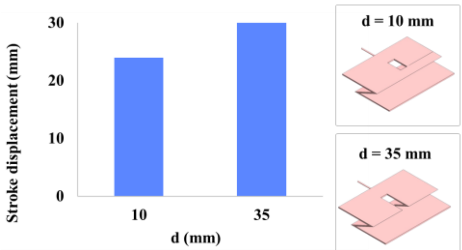

Figure 4. FEM Results for the Stroke Displacement at Different d Values

properties; the actuator was meshed using shell elements, while the clothing was modeled using solid elements. Internal air pressure was applied to the actuator, as shown in Figure 2 d), and appropriate contact interactions were defined between the actuator and its surroundings to prevent penetration. The simulation was conducted in two stages: first, a gradually increasing tensile force was applied to the clothing to simulate pre-stretching; then, a pressure load was applied to the actuator, ramping up to 200 kPa.

IV. RESULTS

One of the representative results is presented in Figure 3, which compares stroke displacement between two actuator configurations with different fold distances: d = 10 mm and d = 35 mm. The figure highlights a clear difference in displacement behavior, demonstrating that the geometry of the fold has a significant impact on actuator performance. Specifically, the actuator with the smaller d value exhibits a reduced stroke, while the larger d allows for a greater change under the same pressure input. This comparison provides insight into how the structural parameters of the actuator influence its mechanical output. Although not shown in this paper, additional experimental trials were conducted to measure output force under varying pressures and configurations. These data further support the role of fold geometry in shaping both the displacement and force characteristics of the actuator.

V. CONCLUSION AND FUTURE WORK

A fabric-based, lightweight, and thin pneumatic shear actuator was developed and analyzed for use in wearable haptic devices aimed at delivering more intuitive skin-stretch feedback with fewer actuators. As a direction for future work, an experimental setup is needed to compare the performance of the shear actuator with conventional compression-based haptic displays, as illustrated in Figure 4. The current shear actuator is limited to one degree of freedom, producing motion only along the x-axis, whereas compression-based displays can deliver directional cues in both the x and y directions through the coordinated actuation of multiple elements. Despite this limitation, the shear actuator aims to reduce the total number of actuators and minimize the spatial gap between stimulation points. In compression-based arrays, closely packed actuators are required to generate the sensation of motion, but perceptual continuity can be disrupted by actuator spacing and variability in tactile resolution. The working hypothesis is that the shear actuator, even with reduced DOF, can provide a more continuous sense

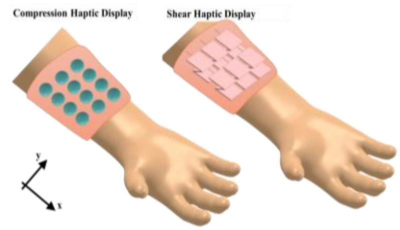

Figure 3. Experimental Setup to Test the Difference Between Normal Pressure Display and Shear Display

of directional motion and potentially greater comfort through lateral skin stretch.

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