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Compact Multimodal Pneumatic Actuator Modules for Distributed Tactile Feedback*

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***Abstract*— This work presents a compact, modular pneumatic actuator capable of providing multimodal tactile feedback, including vibration, impact, and static pressure. Designed for wearable applications, actuator modules can be spatially configured to render tactile patterns on the skin. A user study with four actuators placed on the forearm was conducted to evaluate the perception of different spatial and temporal stimulation patterns. The results show high recognizability for linear and radial step sequences, indicating a strong potential to convey intuitive directional cues. Future work will explore the integration of additional feedback modalities, such as thermal cues and multimodal sequencing, to enhance the expressiveness and realism of tactile interactions.**

I. Introduction

Haptic technology continues to evolve as a critical component in enhancing user interaction across virtual and augmented reality systems, teleoperation, and assistive interfaces to ensure an immersive and realistic user experience [1], [2]. Among the many modalities explored, tactile feedback is notable for its ability to deliver rich localized sensations that significantly enrich user experience [3], [4]. A growing body of research has demonstrated the potential of tactile actuation to simulate textures, impacts, and environmental interactions, with an increasing emphasis on portability and wearability [5].

Despite these advances, most wearable tactile devices rely on a single actuator type, such as vibration motors, piezoelectric elements, or voice coils [6]. This constraint limits their ability to render complex tactile sensations that involve combinations of pressure, impact, or spatial patterns—capabilities that are critical in scenarios such as simulating debris impact in virtual environments, delivering localized alerts, or creating illusions of motion across the skin. Moreover, many conventional devices are either too bulky or lack the mechanical strength needed to produce compelling effects at small scales [7].

This work introduces a modular, miniature pneumatic tactile actuator system designed to overcome these limitations. Each unit is compact, lightweight, and capable of rendering three distinct forms of tactile feedback: vibration, impact, and static pressure. The modular design allows multiple actuators to be arranged in arrays or patterns, enabling the delivery of spatiotemporal haptic illusions such as motion sweeps, multi-point impacts, or directional cues across the skin. Furthermore, the pneumatic approach offers advantages in terms of mechanical simplicity, force output, and scalability across different surface areas of the body.

Our goal is to explore a reconfigurable, customizable tactile system that supports a broader spectrum of haptic expressions while remaining suitable for wearable use. The proposed design opens pathways for diverse applications including VR/AR immersion, tactile communication interfaces, and sensory substitution systems. Preliminary prototypes and actuation tests are presented, highlighting the potential of modular pneumatic units in creating high-fidelity, distributed tactile feedback.

II. Description of the Proposed Setup

A. Design of a single unit

The proposed tactile actuator module features a compact form factor of $15 \times 16 \times 6$ mm, making it well-suited for dense, wearable haptic feedback. Its structure is composed of a 3D-printed ABS enclosure that houses a central air chamber and includes an integrated hose port for pneumatic input. At the core of the module lies a soft silicone air cell, fabricated from Ecoflex 00-30, chosen for its high elasticity and ability to withstand repeated pressure cycles. This air cell is bonded to the internal walls of the chamber using adhesive, creating a sealed and mechanically robust unit. When actuated, the system can deliver vibration, impact, and static pressure feedback, enabling a single module to produce diverse tactile sensations in response to dynamic control inputs. We used the same pnaumatic control setup as described in the literature [8]. The design of the proposed actuator is illustrated in Fig. 1(a).

B. Mounting mechanism

To enable modular integration of pneumatic tactile actuators on various body sites, we designed a versatile mounting system using custom 3D-printed brackets with two attachment options: Velcro straps and skin-safe tape. The brackets allow quick actuator insertion, minimize cable exposure, and include a 3mm spacer to prevent unintended skin contact when inactive. Velcro is ideal for cylindrical areas, while tape ensures secure, low-irritation attachment on flat surfaces. This dual-mount system supports diverse body geometries while preserving tactile feedback fidelity (Figure 1(b)).

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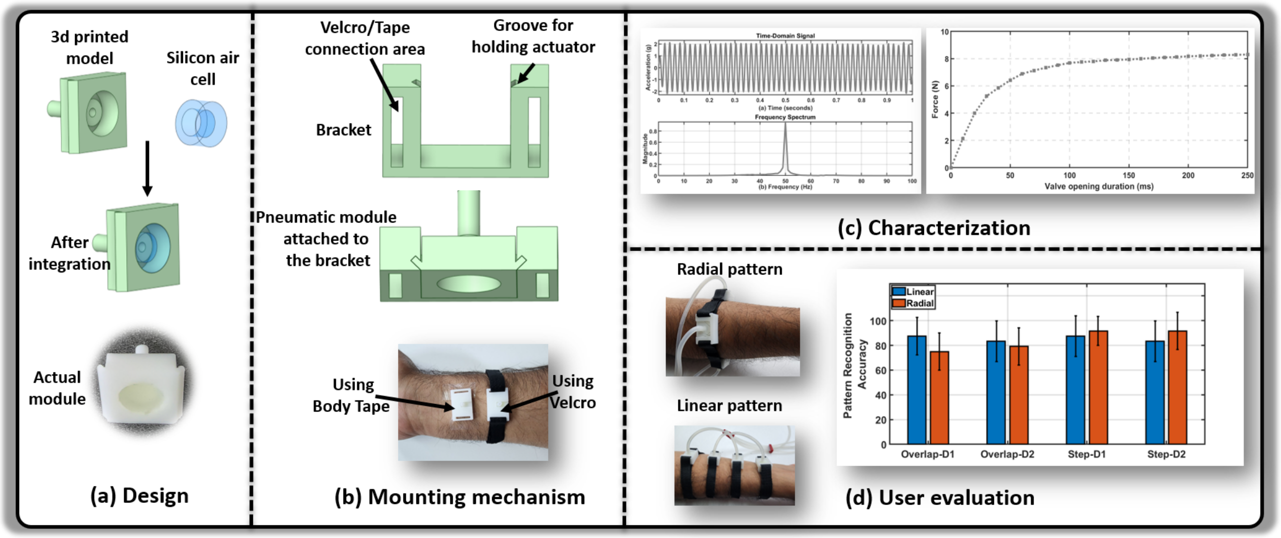

Fig. 1. Overview of the system design, integration, and evaluation. (a) Design of the actuator module with integrated silicone air cell. (b) Mounting using Velcro or body tape. (c) Characterization of vibration (example: 50 Hz vibration) and pressure outputs. (d) User evaluation showing forearm pattern configurations and recognition accuracy.

C. *Characterization*

The actuator was evaluated for vibration and pressure feedback. Vibration was generated by alternating solenoid valve states, and acceleration was measured using an ADXL335 sensor. The results showed perceptible vibration across a wide frequency range ($20-250$ Hz), with amplitudes of 2.64 g to 0.35 g. Pressure feedback was characterized using a force sensor at 10 psi, yielding up to 8.3 N of normal force through controlled valve timing (Figure 1(c)). Both static and impact pressure modes were validated, confirming the actuator's effectiveness for multimodal tactile feedback within safe operational limits.

III. User Evaluation

To assess the perceptual effectiveness of the actuator array, we conducted a user study with 8 participants (ages 24–31) using four pressure modules on the forearm to render four distinct tactile patterns: linear or radial, delivered via step or overlapping sequences. Participants, blindfolded and wearing headphones, identified direction and described the sensation of each pattern. Results showed high recognition accuracy for linear and radial-step patterns, while overlapping radial patterns were less distinct (Figure 1(d)). Step sequences were often described as tapping or walking, whereas overlapping sequences evoked gliding or continuous motion. These findings support the actuator system's potential for delivering expressive tactile cues in wearable applications.

IV. Dicussion and Future Work

Results from our preliminary user study demonstrate that spatially distributed pneumatic actuators effectively convey recognizable tactile patterns. Participants were able to reliably interpret directional cues and distinguish between step and overlapping activation sequences, indicating that the system supports both segmented and continuous sensations, such as "tapping" or "gliding." These interpretations suggest the potential for the actuators to simulate real-world tactile interactions in an intuitive manner.

In future work, we plan to expand these studies by exploring multimodal tactile feedback that combines vibration and pressure delivered either simultaneously or sequentially. We will also investigate how actuator spacing and the temporal order of activation influence perception. Additionally, integrating thermal feedback will be explored to assess how temperature variations can enhance realism and emotional resonance in tactile experiences. These directions aim to improve the design of richer, more immersive haptic systems.

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