Pinching Tactile Display: End-to-end Transmission of Fabric Roughness via Electrostatic Adsorption

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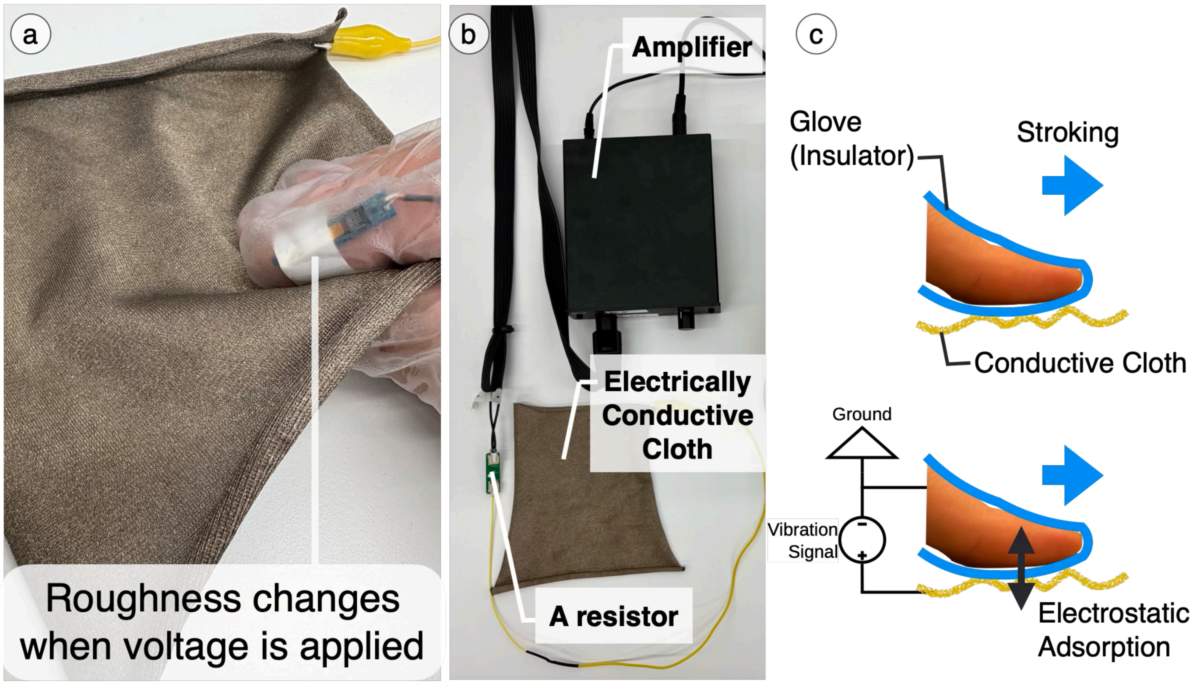

Figure 1: Pinching Tactile Display overview and system configuration. (a) Overview of the display concept: tactile sensation is modulated by manipulating electrostatic adsorption between the conductive fabric and the user's finger, enabling texture variations (primarily perceived roughness) during fabric exploration gestures. (b) System configuration for end-to-end vibration transmission: the input vibration signal is amplified and applied to the conductive cloth, enabling presentation of vibration signals recorded from fabric. (c) Principle of the Pinching Tactile Display: the applied high voltage attracts and controls small electric currents flowing within the finger, so that users perceive the fabric's tactile sensation as if it has changed.

Abstract

Transmitting fabric tactile sensation is difficult because of fabric's complex properties: softness, delicacy, and a relatively uniform surface texture. We propose Pinching Tactile Display (PTD), a conductive fabric system that enables end-to-end transmission of vibration signals measured from fabric. In a user study, we found that perceived roughness can be modulated within 2.1–3.0 on a Likert scale (suggestively comparable to fine-textile differences), and that this modulation arises from voltage-driven bumpiness and frequency-driven stickiness, with largely additive effects. We also found a clear correlation between input vibration signals and finger vibrations, demonstrating that input vibrations are reliably transmitted to the user's finger. These results validate the system as a viable approach for end-to-end fabric tactile transmission and point to potential applications such as remote fabric exploration, VR, and fashion e-commerce.

CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; Interaction devices.

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Keywords

electrostatic adsorption, haptic display, fabric tactile sensation, vibration transmission, end-to-end tactile interface

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1 Introduction

Fabric tactile sensation is challenging to transmit remotely due to the complex mechanical and perceptual properties of textiles—including softness, delicacy, and fine surface structure. Previous end-to-end transmission systems, such as the TechTile Toolkit [4], have focused on rigid objects and hard surfaces, rarely addressing the distinctive properties of fabrics. Telextiles [3] achieved end-to-end remote transmission of fabric tactile sensation using a roller-based device, but it presented only 16 discrete fabric samples and could not provide continuous modulation to convey subtle differences in fabric feel. An existing electrostatic fabric display [2] could only present tactile sensation via unipolar pulse waves, so the input could not be actual tactile data.

We therefore introduce Pinching Tactile Display (PTD), a conductive fabric system that transmits vibration signals measured from fabric via electrostatic adsorption for end-to-end display of fabric tactile sensation. Unlike the prior system limited to unipolar pulse waveforms, PTD accepts measured fabric vibration as input. We report two evaluations: a quantitative study of how voltage and frequency affect perceived dimensions in two aspects—fabric tactile properties (roughness, thickness, stiffness, warmth) and electrostatic adsorption properties (bumpiness, stickiness, pleasantness, friction)—and a correlation analysis showing reliable transmission to the finger and distinguishable patterns for matching signals. Together, these results validate PTD for remote fabric tactile exploration.

2 System Configuration

We use an amplifier to apply voltages to a conductive cloth (Figure 1(b)). The conductive cloth was approximately 30 $cm \times 30$ cm, made of 100% silver fiber, with an electrical resistance of 1 Ω, electromagnetic shielding 60 dB, weight 90 g/m^2, and thickness 0.232 mm (same specification as the prior system [2]). Figure 2 shows the circuit for applying vibration signals to the cloth. The system consists of a conductive cloth, a circuit with a resistor (620 $k\Omega$), and an amplifier. The input vibration signal is amplified and then applied to the conductive cloth. To ensure the current does not exceed 0.5 mA even when 300 V is applied, a resistor of around 600 $k\Omega$ is used [7]. Unlike a unipolar-only configuration, this setup allows both positive and negative voltages, resulting in a bipolar voltage being applied to the cloth.

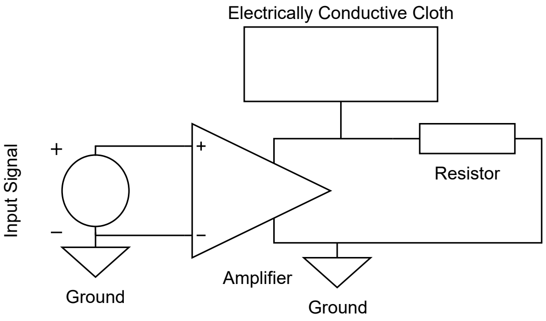


Figure 2: Circuit for applying vibration signals to the conductive cloth. The input signal is amplified and applied to the cloth via a series resistor (620 $k\Omega$) to limit current; the setup allows bipolar voltage for end-to-end vibration transmission.

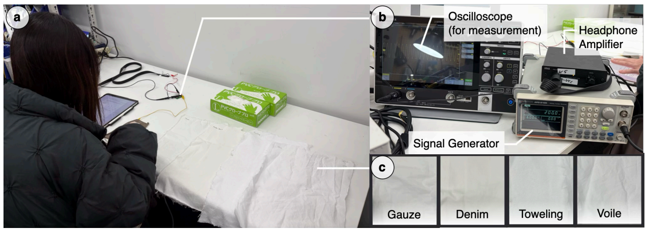


Figure 3: Experimental setup for the quantitative assessment of tactile modulation (Evaluation 1). (a) Overview. (b) Signal generation system. We used signal generator to generate sinusoidal waves, and an amplifier to apply voltages to the conductive cloth. (c) Four reference fabrics (jeans, voile, gauze, towels) used as anchors for the fabric tactile dimensions (Table 2).

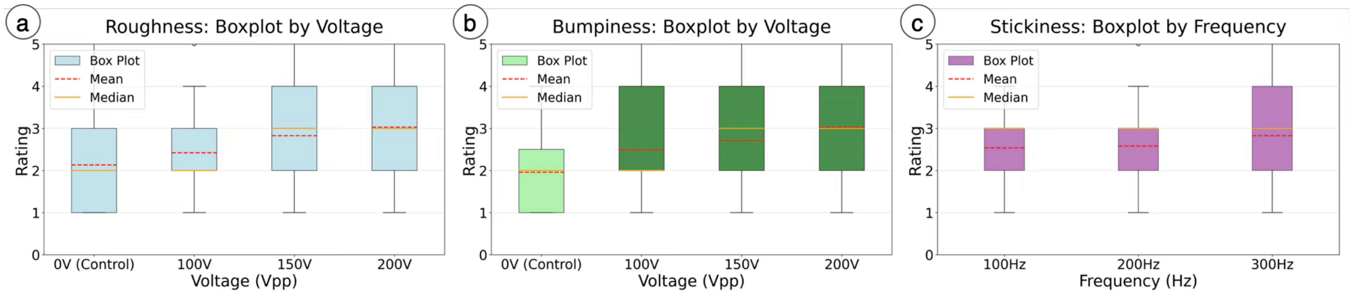
3 Evaluation: Quantitative Assessment of Tactile Modulation

To quantitatively evaluate how voltage and frequency affect users' perceptual ratings, we conducted a user study with 23 participants. We asked participants to rate four fabric tactile dimensions (rough, thick, stiff, warm), following prior work on textile perception [5], and four tactile properties from electrostatic adsorption (bumpy, sticky, pleasant, friction) [1], each on a 5-point Likert scale. We manipulated voltage (100 Vpp, 150 Vpp, 200 Vpp; control: 0 Vpp) and frequency (100 Hz, 200 Hz, 300 Hz) with sinusoidal waves; these ranges were chosen to span perceptually distinct levels within safe current limits and hardware constraints [2]. The design was a two-factor (Voltage × Frequency) full factorial within-subjects design (Figure 3). For the four fabric tactile dimensions (rough, thick, stiff, warm), we provided four reference fabrics (jeans, voile, gauze, towels); participants compared each condition to these fabrics and chose the most appropriate score on a 5-point scale for each dimension, as defined in Table 2 [2]. The four electrostatic adsorption properties (bumpy, sticky, pleasant, friction) were rated on semantic differential scales without physical fabric anchors [1].

Table 1: P-values for voltage, frequency, and interaction effects across eight tactile dimensions. Voltage had a significant main effect on roughness and bumpiness; frequency had a significant main effect on stickiness; no significant interaction effects were found (all $p > 0.05$).

Effect	Rough	Thick	Stiff	Warm	Sticky	Bumpy	Pleasant	Friction
Voltage	0.037^{*}	0.314	0.528	0.192	0.806	0.024^{*}	0.640	0.413
Frequency	0.885	0.577	0.430	0.138	0.025^{*}	0.867	0.640	0.439
Interaction	0.355	0.658	0.528	0.291	0.892	0.867	0.640	0.562

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$, $^{\cdot}p < 0.1$

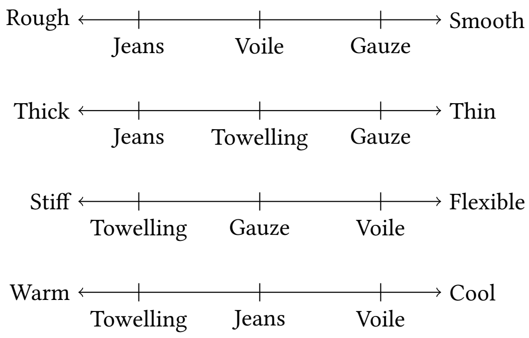

Roughness: Boxplot by Voltage

Bumpiness: Boxplot by Voltage

Stickiness: Boxplot by Frequency

Figure 4: Detailed ratings analysis. (a) Boxplot of roughness ratings by voltage level. (b) Boxplot of bumpiness ratings by voltage level. (c) Boxplot of stickiness ratings by frequency level.

Table 2: Mapping of reference fabrics to the four fabric tactile dimensions (bipolar scales). Participants used these fabrics to anchor their 5-point ratings for roughness, thickness, stiffness, and warmth only; electrostatic adsorption properties were not anchored with physical fabrics.



Since we could not assume normality, we applied the Aligned Rank Transform (ART) [8] and conducted a two-way ANOVA. Post-hoc pairwise comparisons (Hommel's method) were performed when main effects were significant.

3.1 Results

Our analysis revealed statistically significant effects (Table 1). Voltage had a significant main effect on roughness ($p = 0.037$) and bumpiness ($p = 0.024$); frequency had a significant main effect on stickiness ($p = 0.025$). No significant interaction effects were found (all $p > 0.05$). Post-hoc pairwise comparisons (Hommel's method) showed significant differences for these main effects (e.g., roughness: 200 Vpp vs. 0 Vpp; bumpiness: 200 Vpp vs. 0 Vpp; stickiness: 300 Hz vs. 100 Hz), consistent with the main-effect interpretation.

In our detailed ratings analysis (Figure 4), roughness varied between 2.13 and 3.03 across voltage conditions (0 Vpp: mean 2.13, SD=1.29; 200 Vpp: mean 3.03, SD=1.38). The four fabric tactile dimensions were anchored to the reference fabrics (Table 2); for roughness in particular, the range 2.13–3.03 is tied to gauze/voile and related materials by design. We found that voltage modulates bumpiness and frequency modulates stickiness, so tactile sensation can be controlled via these two parameters. In human perception of fabric touch, these changes are experienced as differences in roughness; the two parameters contribute additively to this roughness-related perception.

4 Evaluation: Input-Output Vibration Relationship

We conducted a correlation analysis to verify whether input vibrations properly transmit to output vibrations and whether different inputs produce distinguishable patterns.

4.1 Experimental Setup

We recorded vibration signals from three fabric samples representing different bumpiness levels: Satin (Smooth), Tweed (Intermediate), and Lace (Bumpy) from a fabric sample book [6]. We focused on bumpiness-level variation because bumpiness showed a strong voltage-driven effect in Study 1. We collected vibration data using a robotic arm; sliding speeds were set to 5 levels in 10 mm/s increments within 20–60 mm/s. The signals were then looped, amplified, and applied to the conductive cloth. We measured finger vibrations using a biodegradable piezoelectric sensor (Picoleaf, Murata

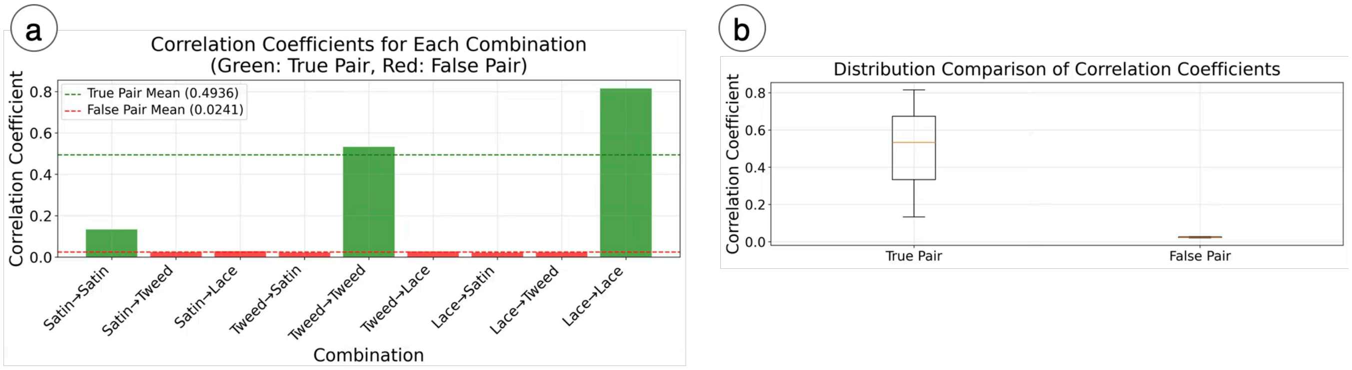


Figure 5: Robotic cross-correlation analysis. (a) Correlation coefficients for each combination. Matching pairs (same fabric) exhibit significantly higher correlations than mismatched pairs (different fabrics). For each template, the correct signal fabric showed the highest correlation, and the template matching algorithm achieved 100% identification accuracy (3/3 templates correctly identified their matching signals). (b) Distribution comparison of correlation coefficients (True Pair vs False Pair). The correlation coefficients for matching pairs (mean $r = 0.494$, SD = 0.342) were approximately 20.6 times higher than those for mismatched pairs (mean $r = 0.024$, SD = 0.003), demonstrating that matching inputs yield higher input–output correlation than mismatched inputs. An independent samples t-test confirmed that matching pairs had significantly higher correlations than mismatched pairs (t = 3.628, $p = 0.008$).

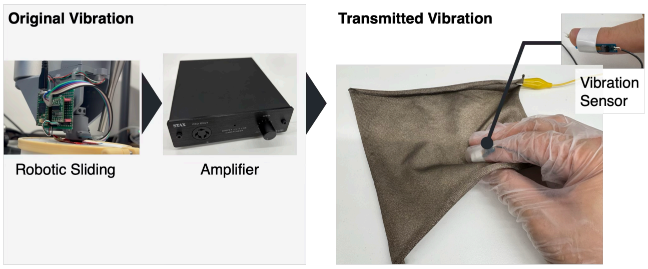


Figure 6: Experimental setup for the input–output vibration relationship (Evaluation 2). Finger vibrations were measured using the Picoleaf sensor (biodegradable piezoelectric sensor) [9] attached to the fingertip while participants rubbed the electrified cloth.

Manufacturing Co., Ltd.) [9] attached to the fingertip. This sensor, made of poly(L-lactic acid) (PLLA), responds sensitively to small deformations and maintains stable output during measurement. Participants rubbed the electrified cloth 30 times while we recorded finger vibrations (Figure 6).

4.2 Analysis Method

To verify whether vibrations similar to the input signal appear in the finger vibrations, we analyzed correlations between input audio signals and finger vibrations. We extracted segments where voltage was applied and finger vibrations were enhanced, and used participant-averaged correlations (one value per participant per fabric) for matching vs. mismatched pair comparisons. We compared matching pairs (same fabric) and mismatched pairs (different fabrics) using an independent samples t-test, and checked against 100 randomly selected segments to confirm correlations were not due to chance.

4.3 Results and Discussion

Our correlation analysis (Figure 5) showed that matching pairs (same fabric) had mean correlation $r = 0.494$ (SD = 0.342) between input and finger vibrations, approximately 20.6 times higher than mismatched pairs ($r = 0.024$, SD = 0.003). An independent samples t-test confirmed that matching pairs had significantly higher correlations than mismatched pairs (t = 3.628, $p = 0.008$).

5 Discussion

5.1 System Capabilities

We show that the system successfully enables end-to-end tactile transmission by accepting vibration signals measured from fabric as input and showing a 20.6-fold correlation difference between matching and mismatched pairs. This demonstrates that different fabric input signals produce distinguishable finger vibration patterns at the sensor level, consistent with input-driven differences in the transmitted signal; perceptual identification by users was not tested in this evaluation.

5.2 Applications and Limitations

Potential applications include remote fabric exploration, VR, and fashion e-commerce—e.g., transmitting recorded vibration signals to the display so users can feel fabric-like feedback at a different location or in virtual environments. These scenarios were not implemented or evaluated in the current work.

Current limitations include the need for gloves, limited modulation to roughness/bumpiness/stickiness, and high voltage requirements (we used up to 200 Vpp in the evaluation). Future work should explore glove-free operation and extended modulation capabilities.

6 Conclusion

We presented Pinching Tactile Display (PTD), a conductive fabric system that enables end-to-end transmission of vibration signals measured from fabric through electrostatic adsorption. In a user study, we showed that perceived roughness can be modulated between 2.1 and 3.0 on a Likert scale (suggestively comparable to fine-textile differences such as gauze vs. voile), and that this modulation arises from voltage-driven bumpiness and frequency-driven stickiness, with largely additive rather than synergistic effects. A correlation analysis demonstrated that input vibrations are reliably transmitted to the user's finger, with matching pairs showing approximately 20.6 times higher correlation than mismatched pairs. These results validate PTD as a viable approach for end-to-end fabric tactile transmission and point to potential applications such as remote fabric exploration, VR, and fashion e-commerce.

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