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Exploring Fingertip Slip Feedback for Haptic Augmentation and Referral Using Thermal Feedback

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***Abstract*—Thermal feedback offers new possibilities for enhancing user experience by combining with vibrations. Yet, little research has explored haptic augmentation and referral through thermal feedback with texture slip feedback on the fingertip. To address this gap, we examined variations in tactile perception and the potential for the thermal referral phenomenon on the fingertip by integrating thermal and texture slip feedback. Using a custom haptic device, we delivered thermal stimuli ranging from 24 to 40°C alongside slip feedback related to three distinct textures (silk, felt, sandpaper) to the middle and distal phalanx of the fingertip, respectively. Participants assessed the perceived intensity, warmness, roughness, and stickiness of the integrated tactile feedback and identified the perceived location of the thermal sensation. Our results showed that thermal feedback can affect the roughness of intermediate texture (felt), increasing the median roughness rating from 43.5 to 60 on a 0–100 scale under cold and hot conditions, respectively. Furthermore, the occurrence rate of thermal referral increased as temperature increased (79.8% at a hot condition). We discuss the efficacy of thermal feedback in augmenting texture slip feedback and haptic referral and highlight implications for future research.**

***Index Terms*—Texture, Slip-feedback, Thermal feedback, Haptic AR, Thermal referral.**

I. Introduction

Over the last decades, extensive research has focused on effectively rendering virtual texture scanning. The conventional methods utilized the vibrotactile feedback to convey surface information based on users' scanning motion, using vibrations of single sinusoids or complex spectrum [1], [2]. Another approach involves generating slip feedback by rotating a textured medium, such as cylinder [3], [4], sanded ball [5], and disk [6], [7], achieving high realism in scanning of infinite surfaces. Both methods effectively rendered the fine textures' roughness by stimulating the Pacinian corpuscle (PC) [8] or activating both PC and rapidly adapting (RA) fibers [9]. These approaches lack the ability to deliver temperature feedback, which plays a critical role in material perception. Due to the bulky form factor resulting from integrating a thermal actuation system with a texture rendering device, adopting thermal texture rendering remains challenging.

Recent work reported a thermal referral, which is the phenomenon that the location of the thermal feedback is perceived as being transferred or spread to the site of haptic stimulation, such as vibrotactile feedback [10] or ultrasound waves [11]. Given that texture scanning involves vibrations caused by the fingertip's ridge colliding with texture elements [12], we hypothesized that the thermal sensation applied to the middle phalanx of the index finger could be perceived at the distal phalanx, fingertip, where the texture feedback is delivered. If this thermal referral effect is validated, it could open new possibilities for rendering textures with temperature. In addition, Choi et al. reported that mechanical modulation of the fingertip tissue by thermal stimuli could modify the texture's friction perception [13]. To investigate whether this perception variation is due to modulation of the skin's physical properties or perceptual biases (such as cold-induced imagery affecting perceived slipperiness and smoothness), we examined the effects of integrated haptic feedback, which combines thermal and texture sensations delivered to different locations, on tactile perception.

To test our hypothesis, we developed a custom desktop haptic device capable of providing thermal and texture feedback to these two phalanges. By adopting the compact textured disk mechanism as described in [6], our device's disk attaching three different textures (silk, felt, sandpaper) rendered the slip-feedback with three scan speeds (30, 60, 90 mm/s), and the thermal system delivered five temperatures ranging from 24 to 40°C. We conducted two experiment sessions to investigate the effects of integrated haptic feedback on (1) perceived intensity (PI) and three texture perception dimensions—warmness, roughness, and stickiness—and (2) the location of the perceived thermal stimuli. Our findings demonstrated that the perceived roughness of the intermediate rough texture could be enhanced by the temperature applied at a different location (from 43.5 to 60 on a 0–100 scale) and the high possibility of thermal referral across all textures under a hot temperature (79.8%). We envision that thermal referral induced by integrated haptic feedback can expand conventional texture interactions by modulating the perceived roughness

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and warmness. Our research also contributes to enlarging the scope of haptic AR [14] and traditional VR by simulating a novel method for surface scanning of temperature-integrated textures, opening up new methods for immersive and interactive experiences.

II. Implementation

We designed a custom-built desktop device to deliver thermal feedback to the middle phalanx and slip feedback to the distal phalanx of the index finger, using a compact textured disk rotating concentrically (see Fig. 1).

A. Hardware Design

The device's body part is configured with a cover, a Peltier module, a gear motor, a bracket, a heat sink with a fan cooler, and supports (Fig. 1 (A)). The gear motor (Adafruit; N20 DC motor with 298:1 gear ratio) was mounted in the body using a bracket and supports. A disk ((∅) 15 × (L) 11.5 mm) was engaged with the gear motor shaft, attaching a texture on it using double-sided tape (Fig. 1 (B)). We added a force-sensing resistor (Interlink; FSR-402) between the two supports to measure the contact force applied to the disk. The components were vertically aligned to transmit the pressing force to the sensor.

The heat sink, to which the Peltier module (Multicomp; MCPE-071-10-13; (W) 20 × (L) 20 × (D) 3.6 mm) was affixed using thermal grease, was securely positioned inside the body through the cover part. A thermistor (Mouser Electronics; 223Fu3122) was attached to the outer edge of the Peltier module's upper surface for precise temperature control. The cover was designed to restrict the contact area ((W) 16.75 × (L) 71.5 mm) by covering the outer edge of the Peltier module, preventing the thermistor from measuring skin temperature. The cover, bracket, disk, and supports were 3D-printed using Poly Lactic Acid (PLA). The final device has a dimension of (W) 55.5 × (L) 82.75 × (D) 44.5 mm and weighs 153.8 g.

B. System Architecture

The host PC ran a Unity application, transmitting the temperature and rotation commands via USB serial communication with 115,200 bps. By the received commands, an Arduino Mega controlled the gear motor and Peltier module via a dual motor driver (Pololu; TB6612FNG). To provide natural texture sensation through the fingertip contact with the rotating disk, we referred to the previous work [6] and rotated the fingertip-sized disk at angular velocities (W) corresponding to the 36% of the hand movement speed (V) and disk radius (R = 7.5 mm), based on the relationship: $0.36V = RW$. The thermal and rotation feedback were controlled using a PID loop at 1 kHz with the Arduino MCU.

III. User Study

We investigated the effects of integrated thermal and slip feedback on four dimensions of tactile perceptions in the first study session and the occurrence rate of thermal referral in the second session. The studies were approved by the Institutional Review Board at GIST (20241112-HR-EX-001).

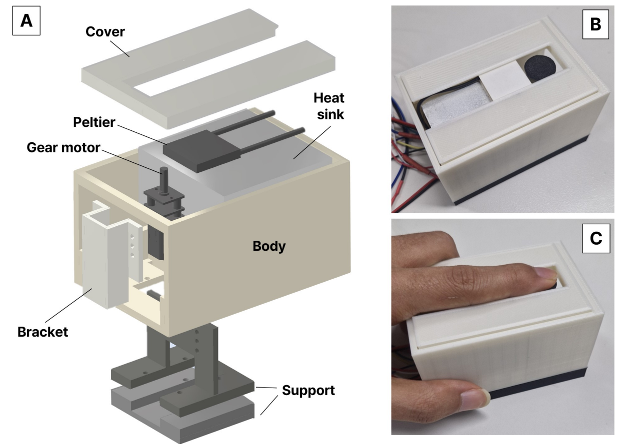

Fig. 1. (A) Exploded view of our custom desktop device (B) Perspective view of our system attaching sandpaper on the disk. (C) A grasping scene using passive touch. Participants contacted the middle and distal phalanges of the index finger to the Peltier module and textured disk, respectively.

A. Experiment Design

The experiment conditions of three textures, three scanning speeds, and five temperatures were consistent across the two sessions. Regarding the textures, we selected 120-grit sandpaper, felt, and silk for the rough, intermediate, and smooth sensation referring [15].

We selected 30, 60, and 90 mm/s for the scanning speeds, which were commanded as 1.44, 2.88, and 4.32 rad/s for angular speeds, respectively. In detail, 30 mm/s was determined through a pilot test with three users as it achieved consistent disk rotation while enduring the fingerpad pressure. To encompass a wide range of scanning speeds but remain close to the reported average texture scanning speed of 50 and 52 mm/s [5], [16], we selected 60 mm/s as the medium speed condition. Applying the same interval between the slow and medium speeds, we determined 90 mm/s as the fast speed condition ensuring less than the reported maximum scanning speed (120 mm/s) [16].

For the temperature, we selected 24°C (cold), 28°C (cool), 32°C (default), 36°C (warm), and 40°C (hot). We defined 32°C as a default condition referring to the previous report [17]–[19], then applied the same temperature interval of +/- 4°C as in [17], [20]. The pain thresholds reported in the literature were 9 [19] and 44°C [21], therefore, our cold and hot conditions were outside the pain range which was ensured from a pilot test with three participants. We maintained the environment temperature at 24°C with a humidity level above 30%, ensuring participants perceived 32°C as neutral and constraining for external environmental influences [22].

We recruited twelve participants (7F/5M, age 20–26, M: 21.8, SD: 1.5) who reported no abnormality in tactile sensitivity. Due to the experimental fatigue, the total 180 trials (3 scan speeds × 5 temperatures × 3 textures × 2 repetitions × 2 sessions) were divided into three blocks by the texture type balanced with the Latin squares. Each participant conducted 30 trials per two sessions on a separate day where each day was assigned with the block. The average time required to

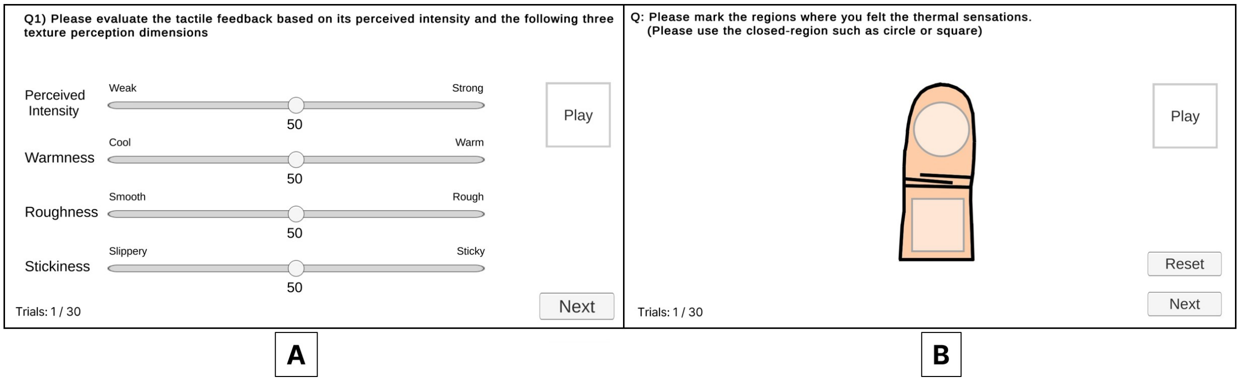

Fig. 2. GUIs (A) to rate Perceived Intensity, Warmness, Roughness, and Stickiness from top to bottom using the slider, and (B) to specify the area where thermal sensation occurs. Both GUIs include a play button to render integrated haptic feedback and a next button to proceed to the next trial.

complete the first session across three blocks was 70 minutes, while the second session took 65 minutes on average.

B. Experiment Procedure

As contact force is known to influence tactile perception [23], [24], we set the contact force below 3.0 N as the valid range of contact forces for texture perception [25]. Therefore, we instructed the participants to press the disk within the valid force range by providing visual feedback on the FSR sensor readings before every experiment session. During the experiment, a visual warning was provided whenever a force of 0.0 N or above 3.0 N was detected instead of informing the contact force to prevent attention distraction.

Session 1) Tactile Perception: By following the previous work [26], [27] which employed the passive touch, participants perceived the tactile feedback without hand movement while grasping our device using their left hand (Fig. 1 (C)). Before each trial, a waiting screen displayed the message: *"Please lift up your index finger and wait for 20 seconds"*. Morin reported that participants consistently perceived the thermal sensation after interacting with thermal systems, while the cold stimuli required a longer duration (13.7 seconds) [19]. Therefore, we forced participants to wait at least 20 seconds to minimize the potential influence of residual thermal sensations from the previous trial, neutralize the fingertip skin temperature, and allow for precise temperature adjustment of the Peltier module.

We designed the experiment program (Fig. 2 (A)), including GUI buttons and four metrics: perceived intensity, warmness, roughness, and stickiness, as reported in [28]. We collected perceived intensity to evaluate the overall magnitude of integrated tactile feedback. We excluded hardness dimension among the four main texture perceptions because it requires pressing motion, which is unsuitable for static hand motion (passive touch) [29]. Upon clicking the play button, the fully randomized combination of thermal and slip feedback was provided for 15 seconds. Participants assessed the impact of integrated thermal and slip feedback on four metrics using a continuous integer scale ranging from 0 to 100 (default: 50), adjusting the slider with a mouse in their right hand. Participants could proceed to the next trial by clicking the Next button, which became active only after the play button was clicked and the ratings were changed at least once. Participants repeated the above procedure for 30 trials including waiting followed by the evaluation process.

Session 2) Thermal Referral: After the first session, participants took a five-minute break and conducted a second study to investigate the potential of thermal referral on the fingertip by the integrated haptic feedback. We identically replicated the procedure of the first session, except for the responding screen (see Fig. 2 (B)). Participants freely marked the regions where they felt thermal sensations using a mouse drag on the finger image, as in [10], with the constraint of using closed-loop shapes (e.g., circle or square) rather than checkmarks or lines. Upon clicking the next button after dragging the region at least once, the subsequent trial with the waiting screen followed by the evaluation procedure was presented, repeating for 30 trials.

IV. Results

A. Session 1 - Tactile Perceptions

Since none of the ratings for each combination of scan speed and temperature passed the Shapiro-Wilk test, we used Two-way ART-ANOVA [30] to evaluate the impact of scan speeds, temperatures, and their interaction on the tactile perception of the three materials (Table I). Figure 3 illustrates the effects of scan speeds and temperatures on perceived intensity, roughness, warmness, and stickiness by each texture with significantly different pairs. For visual clarity, the results of post-hoc pairwise comparisons were visually specified using alphabetical letters instead of marking the asterisks.

The analysis of scan speeds revealed statistically significant differences in the PI and roughness across all textures, as well as in the warmness perception of the sandpaper. For post-hoc tests, we used the Conover-Iman tests with Bonferroni correction for both PI and roughness. Significant differences in scan speeds existed for PI and roughness across most pairs, except for PI with felt (60 vs. 90 mm/s, $p = 0.36$), PI with sandpaper (60 vs. 90 mm/s, $p = 0.07$), and roughness with sandpaper (60 vs. 90 mm/s, $p = 1.00$). Despite scan speed showing a significant effect on the warmness of sandpaper, the same post-hoc analysis showed no significant differences.

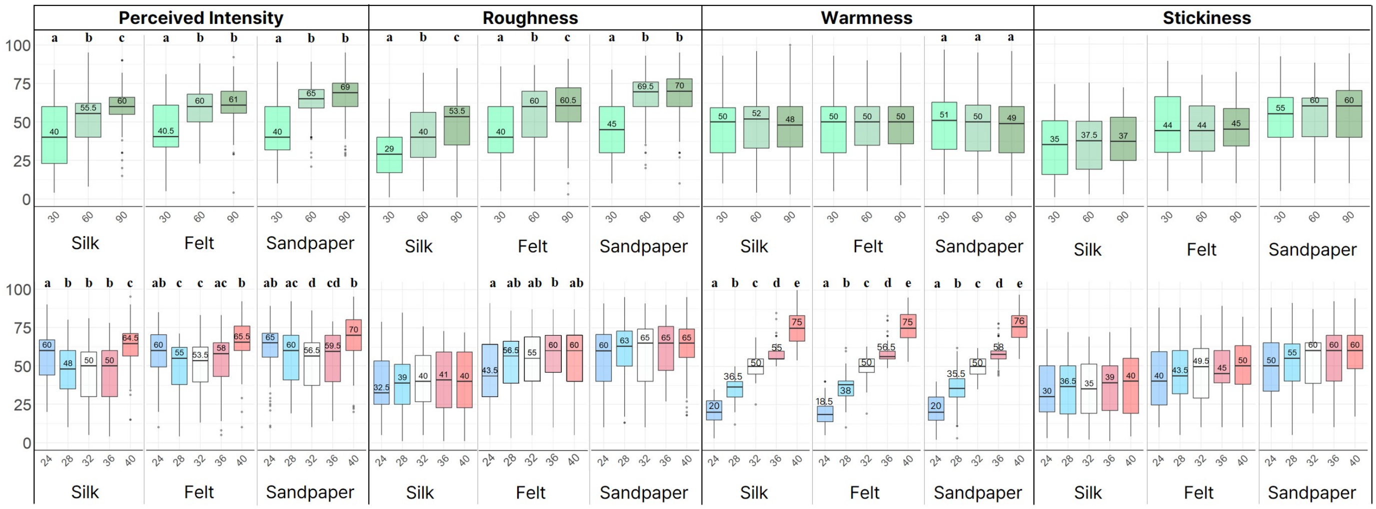

Fig. 3. Box plots showing the perceived intensity, roughness, warmness, and stickiness ratings by textures, scan speeds, and temperatures. (Top) Box plots showing the impact of scan speeds (X-axis) on four metrics (Y-axis). The lighter the color indicates the slower the scan speed, while the darker the color represents the faster the scan speed. (Bottom) Box plots showing four metrics' distribution (Y-axis) by temperatures (X-axis). The blue and red box plots indicate cooler and hotter temperatures, respectively, compared to the default temperature (32°C). The post-hoc analysis results are summarized in alphabets. Groups assigned a distinct single letter (e.g., 'a' and 'b') represented statistically significant differences ($p < 0.05$), while groups sharing a common letter (e.g., 'ab' and 'a') indicated no significant difference ($p \geq 0.05$).

TABLE I
STATISTICS OF TWO-WAY ART-ANOVA

Factor		DF	DF_{res}	PI		Roughness		Warmness		Stickiness	
				F-val	P-val	F-val	P-val	F-val	P-val	F-val	P-val
Silk	Scan speed	2	345	**52.62**	**< 0.001**	**36.75**	**< 0.001**	2.38	0.09	0.76	0.47
	Temperature	4	345	**19.07**	**< 0.001**	0.80	0.53	**609.73**	**< 0.001**	0.44	0.78
	Scan speed x Temperature	8	345	2.30	**0.02**	0.76	0.64	1.60	0.13	0.34	0.95
Felt	Scan speed	2	345	**38.97**	**< 0.001**	**35.30**	**< 0.001**	0.99	0.37	0.71	0.49
	Temperature	4	345	**15.08**	**< 0.001**	**2.56**	**0.04**	**490.74**	**< 0.001**	1.42	0.23
	Scan speed x Temperature	8	345	1.34	0.22	0.31	0.96	1.55	0.14	0.42	0.91
Sand paper	Scan speed	2	345	**96.56**	**< 0.001**	**56.12**	**< 0.001**	**3.10**	**0.05**	0.55	0.58
	Temperature	4	345	**14.33**	**< 0.001**	0.89	0.47	**470.23**	**< 0.001**	1.91	0.11
	Scan speed x Temperature	8	345	1.27	0.26	0.74	0.65	1.03	0.41	0.37	0.94

The temperature had a significant effect on PI and warmness in most pairs and further significantly affected the roughness perception of the felt. The Conover-Iman tests with Bonferroni correction for roughness perception of felt showed statistically significant differences between 24 and 36°C, ($p = 0.03$).

B. Session 2 - Thermal Referral

Based on whether the trajectories crossed the midline of the finger image along the y-axis, we categorized the trajectories into three states: *No referral*, *Referral*, and *Masking*. In detail, trajectories were classified as *No Referral* if they did not cross the midline of the finger image and aligned with the locations where thermal feedback was provided. Conversely, *Masking* was assigned to a trajectory drawn on the fingertip where the slip feedback was provided. A trajectory is classified as *Referral* if it includes two close-loop responses on the thermal- and slip-feedback locations or a single loop crossing the midline. We finally calculated occurrence rates of three states in a specific condition of texture type, temperature, and scan speed (Fig. 4), and visualized the participants' dragged trajectories by overlaying them (Fig. 6).

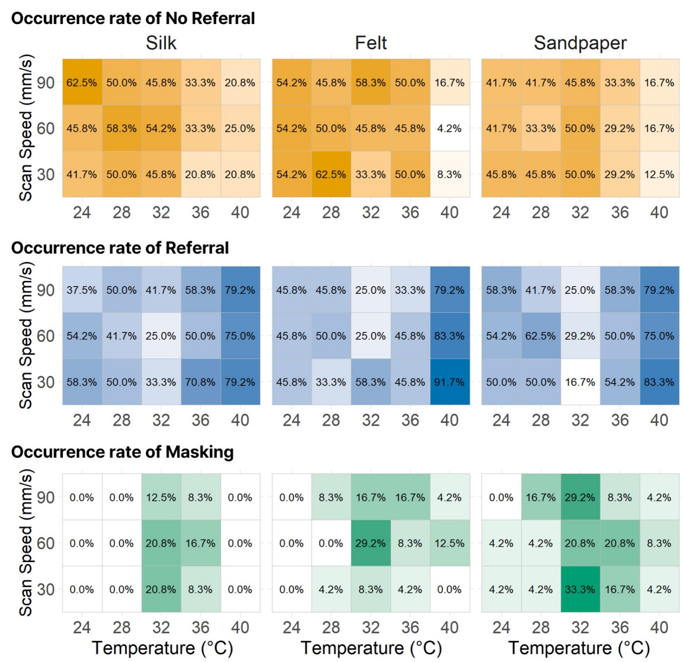

Fig. 4. Tile plots for occurrence rates of three referral states (*No Referral*, *Referral*, and *Masking*) across textures (Silk, Felt, and Sandpaper), scan speeds (30, 60, and 90 mm/s), and temperatures (24, 28, 32, 36, and 40°C). Each row and column indicate the different scan speeds and temperatures, respectively. Darker colors indicate higher occurrence rates.

We further analyzed the occurrence rates to identify which condition of the scan speeds and temperatures significantly influences referral states. We applied the One-way ANOVA to the occurrence rates of *No referral* and *Referral* states by scan speeds and temperatures as they followed the normality, showing that temperature primarily influenced the referral states (Scan speed: F(2, 42) = 0.15, $p = 0.86$; Temperature: F(4, 40)) = 28.38, $p < 0.01$) (Fig. 5). Paired t-test with

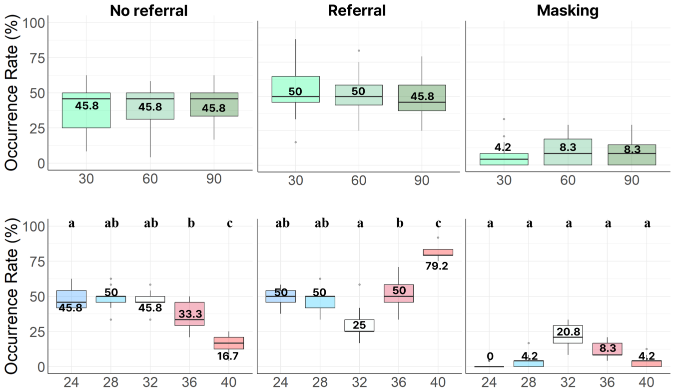

Fig. 5. Box plots showing the occurrence rates (Y-axis) of three referral states (*No referral*, *Referral*, and *Masking*) across scan speeds (30, 60, and 90 mm/s; X-axis, top) and temperatures (24, 28, 32, 36, and 40°C; X-axis, bottom).

TABLE II
PAIRED T-TEST RESULTS WITH SIGNIFICANTLY DIFFERENT PAIRS

Referral state	*DF*	Temperature pair	T statistics	P-value
No referral	8	24 vs. 36	4.75	0.01
		24 vs. 40	9.07	< 0.01
		28 vs. 40	8.87	< 0.01
		32 vs. 40	13.87	< 0.01
		36 vs. 40	4.09	0.04
Referral	8	24 vs. 40	-9.17	< 0.01
		28 vs. 40	-8.48	< 0.01
		32 vs. 36	-3.94	0.04
		32 vs. 40	-14.43	< 0.01
		36 vs. 40	-6.94	< 0.01

Bonferroni correction for *No referral* and *Referral* was applied to the occurrence rate by temperature and summarized in Table II, showing only significantly different pairs. For the *Masking* state, we applied the Friedman test due to the non-normality, which showed a statistically significant difference in temperatures (Scan speed: $\chi^2(2)$ = 2.00, $p = 0.37$; Temperature: $\chi^2(4)$ = 29.06, $p < 0.01$), while Wilcoxon signed-rank test with Bonferroni correction showed no significant differences in any temperature pairs.

V. DISCUSSION

In this paper, we observed the variation of tactile perception except for the stickiness dimension and the potential of the thermal referral by integrated thermal and slip feedback. Based on these, we highlight the efficacy of the integrated feedback in creating opportunities to generate new user experiences and outline implications for design practice.

A. Reflections on User Study

1) Session 1 - Tactile Perception: Our study showed that PI increased linearly with scan speed and exhibited a U-shaped trend across temperatures. The observed linearity between PI and scan speed is attributed to the dependency between rotation speed and the vibration intensity generated by the gear motor. Also, both hot and cold temperatures positively influenced PI compared to the default temperature, indicating that an 8°C variation is required to augment PI.

Notably, scan speed significantly affected roughness perception, contrasting with previous reports of minimal influence [24], [31], [32]. We conjecture that the direct transmission of the gear motor's vibrations to the fingertip would affect the roughness perception. Asano demonstrated that the perceived roughness could be modified by the amplitude of vibrotactile feedback overlaid to the texture sensation [33]. This aligns with our findings that higher gear motor speed increases vibration amplitude, potentially activating the PC channel and enhancing roughness perception. Our results also revealed that the perceived roughness of felt was increased with higher temperature stimuli. This result suggests that the thermal stimuli, provided to a different location with the slip-feedback, can influence the perceived roughness of intermediate textures. The temperature primarily affected the warmness perception, while scan speed showed no significant effect on the warmness. Stickiness perception remained unchanged across scan speeds and temperatures, indicating that the constant scan speed was insufficient to induce variations, while fluctuations in scan speed are necessary to influence this perception as in [5].

B. Session 2 - Thermal Referral

The thermal referral by integrated thermal and slip feedback was observed in the finger and was primarily affected by the temperature, not the scan speed. In detail, Figure 4 and 5 showed that *No referral* state was frequently observed with cold condition, whereas the occurrence rate of the *Referral* state increased with hotter feedback, regardless of textures. Edward reported a higher density of cold receptors (2–4 per cm^2) compared to warm receptors (1.6 per cm^2) in the finger volar [34]. Our results, which revealed a significantly higher occurrence of *Referral* than *No referral* under hot feedback, might have resulted from this unbalanced distribution of thermoreceptors. This interpretation aligns with previous work showing a high rate of thermal referral on the forearm under hot condition [10], where the density of cold receptors (6–7.5 per cm^2) is higher than the warm receptors (0.3–0.4 per cm^2) in the forearm [34]. In contrast to findings on the forearm, where Wang et al. reported a significantly high *Masking* rate ($\simeq$ 55%) under warm conditions [10], we observed consistently lower occurrence rates of *Masking* state on the fingertip (8.3% under warm condition). We attribute this lower *Masking* rate to its higher tactile sensitivity, resulting from denser tactile afferents in fingertip skin (240 per cm^2) compared to the forearm (13 per cm^2) [35]. This heightened tactile sensitivity and thermal stimuli applied locally to a smaller area than the arm might lead to a clear perception of texture sensations over the shifted thermal feedback, thereby suppressing the thermal masking effect. Additionally, our slip-feedback, including the gear-motor induced vibration, stimulated mainly PC and RA channels whereas the prior work used pure vibrations activating PC only. Since the underlying mechanism of the thermal referral remains unclear, further studies are required.

Another notable finding was no significant effect of scan speed on thermal referral, as illustrated in Figure 5 (Top). This result indicates that the thermal referral was predominantly

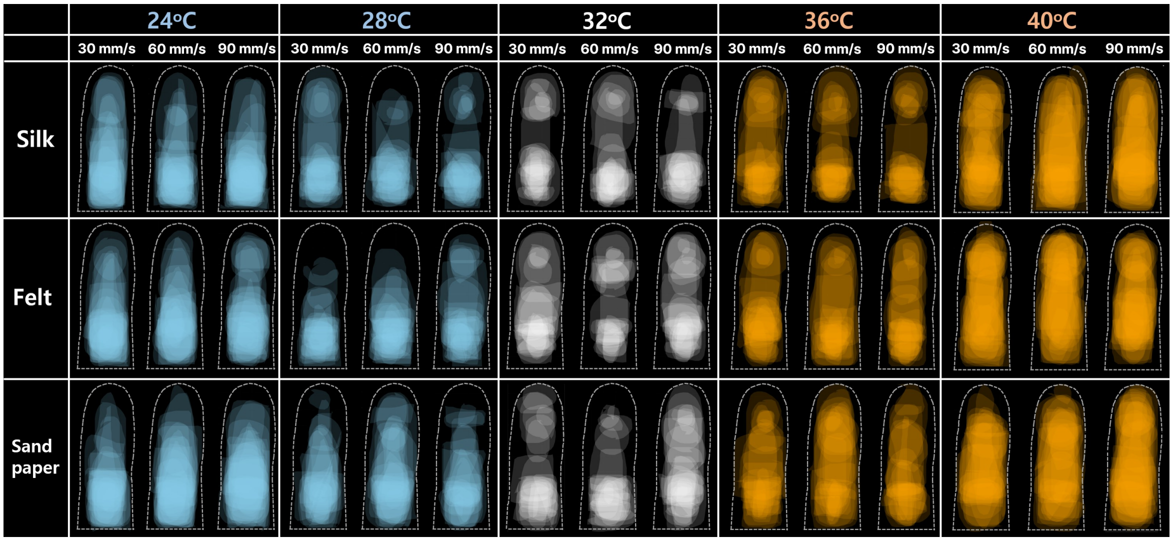

Fig. 6. Overlaid trajectories across participants under a specific tactile-feedback condition. The blue, orange, and white contours indicate the perceived area where cooler, hotter, and default temperature feedback was provided.

affected by the thermal with texture sensation, regardless of the vibration intensity induced by the gear motor. Our finding suggests that thermal referral, traditionally associated with vibrotactile feedback, can also be generated through texture slip feedback at varying scan speeds. Given the small sample size of twelve participants and the in-lab experiment, future work will be required to validate our findings broadly.

C. Implications for Design Practice

Our findings on the perception of the integrated thermal and slip feedback show the following implications:

Thermal referral can occur in fingertip under texture slip feedback. The thermal referral phenomenon has been validated for vibrotactile feedback [10], [36] and ultrasonic wave [11]. Our results extend these observations by demonstrating that thermal referral also occurs in the index finger for the integrated thermal and slip feedback, suggesting various potential applications. The haptic displays, aiming at rendering both temperature and texture, require physical cooling or heating of the texture surface, facing issues of bulky form factor and efficacy, thereby remaining under-explored. Moreover, previous handheld texture displays employed rotating medium [3]–[5], [34], which is unable to effectively heat or cool the textured surface due to the low thermal conductivity. Our finding of thermal referral to the distal phalanx indicates that a thermal perception of texture scanning can be achieved without direct contact between the heated/cooled surfaces and the fingertip. In future work, we will investigate whether thermal referral in texture sensation occurs during active touch and can be utilized for VR applications by simulating the feeling of scanning visually hot or cold surfaces.

Thermal feedback can modify the perceived roughness and intensity. For dynamically modifying the texture roughness, conventional methods have leveraged the vibrotactile feedback [33], [37] or multiple textures attached on the interfaces [3], [4]. We augmented the medium-rough texture's perceived roughness by delivering integrated feedback to different finger locations, enhancing or suppressing it compared to the default temperature. This phenomenon occurs without mechanically modifying the finger tissue via direct thermal feedback [13], therefore we assume that the interactive neural process related to mechanoreceptors and thermal receptors (TRPM3 and TRPM8 for warm and cold, respectively) might affect the modulation [38]. Nevertheless, our novel approach could render the texture with temperature while modulating the perceived roughness of felt or similarly rough textures. Also, the haptic display integrated with the thermal system regulates the perceived intensity by adjusting its temperature, expanding the traditional VR experiences. In addition, as felt elicited the highest referral rates under low scan speed with hot feedback (91.7%) and demonstrated perceived roughness augmentation, future work will examine the generalizability of these findings across diverse sensory modalities.

VI. Conclusion

Our study, employing a custom desktop device, showed that the integrated thermal and texture slip-feedback provided to the different sites of the index finger could modify the various tactile perceptions except for stickiness. We also demonstrated that thermal referral could occur in the fingertip under the slip-feedback with hot temperature. These results suggest that the thermal referral phenomenon can be extended from the conventional vibrotactile feedback to the skin slip feedback. We hope this illusory thermal propagation via slip feedback aids in overlaying temperature on texture and enhancing tactile perception in conventional VR applications.

VII. Acknowledgement

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