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3D Shape Perception through Spatiotemporal Vibrotactile Patterns with Kinesthetic Feedback

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***Abstract*—Haptic feedback has been employed to enhance shape perception during the grasp interaction for improved immersion and task performance in virtual reality (VR). Although wearable devices offer precise multi-phalangeal haptic feedback, their bulkiness and complexity often hinder practicality. In addition, fingertip-based tactile feedback often limits users from feeling the sequential and continuous sensation across the finger surfaces during power grasp. We present a novel haptic shape rendering method synchronizing spatiotemporal vibrotactile feedback across multiple phalanges with low degrees of freedom (DOF) kinesthetic feedback. We generate diverse vibrotactile patterns by leveraging the funneling illusion and modulating vibration duration during the hand flexion. We carried out two user studies to validate the tendency of shape perception with the given haptic feedback in VR. Results demonstrated consistent shape associations and clear user preferences for specific feedback patterns.**

***Index Terms*—3D shape perception, funneling, phantom sensation, haptics, virtual reality**

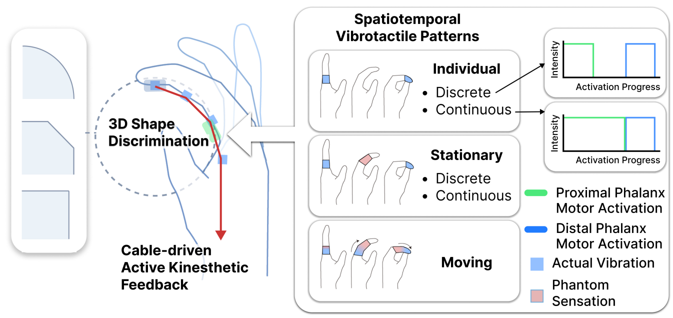

Fig. 1. Proposed haptic rendering method utilizing temporally and positionally modulated vibrotactile patterns with tendon-based kinesthetic feedback for object shape discrimination while grasping virtual objects.

I. Introduction

Haptic feedback plays a fundamental role in how humans perceive the object properties while grasping, which enhances immersion and the performance of virtual interaction. A number of haptic devices have been presented for improving realistic grasp by providing cutaneous feedback including force feedback [1]–[3] or tactile stimulation [4]–[6] on fingertips, and by adjusting overall hand posture through hand-held [7], [8] or wearable devices [9]–[13].

To focus on the role of grasping in shape perception, it is suggested that users typically perceive object shape through two primary grasp types [14]. One is the precision grasp, which requires fine fingertip manipulation, and the other is power grasp, using all phalanges for a robust grip [15], [16]. The realistic reproduction of power grasp sensations through wearable haptic devices necessitates feedback across multiple phalanges. Various wearable devices providing multi-phalangeal sensation for virtual object manipulation have been presented. For delivering cutaneous feedback, prior work developed a glove for distinguishing 3D shapes by collision-based passive vibrotactile feedback [17], albeit with increased mental load from frequent object penetration. Since proprioceptive feedback plays a significant role in discriminating object shapes and sizes [18], wearable devices providing multi-phalanx kinesthetic sensation have been presented, including linkage-based exoskeletons [19], [20], pneumatic glove [21], and the device utilizing reconfigurable materials [22]. However, shape perception through grasping relies on the integration of both cutaneous and proprioceptive feedback from different sensory receptors [2], [18], [23], not the sole sensation. Therefore, recent works have developed multiple phalangeal, multi-modal feedback gloves to provide a more comprehensive experience. These include a tendon-driven mechanism providing both pressure on finger pads and multi-phalanx kinesthetic feedback [24], and a wearable device supporting multi-phalangeal kinesthetic feedback using electrostatic clutches, supplemented by vibrotactile feedback on fingertips [25]. While effective, they were bulky and required complicated mechanisms for precise phalangeal control, causing reduced wearability and comfort. Moreover, prior approaches primarily focused on the tactile feedback at the fingertips, where the system offers instantaneous tactile sensation at the moment of distal phalanx contact. In addition, most existing devices for grasping could provide vibration only at the position where the vibration motor is attached. This often overlooks the rich sensations across the digits or outside the motors, which are experienced during the natural grasp of various shapes.

Instead of providing instant and collision-based vibration feedback, several vibrotactile rendering methods like phantom sensation [26], [27] has been developed for the smooth and gradual haptic experience, requiring fewer actuators to activate a wider range. While several applications of this phenomenon

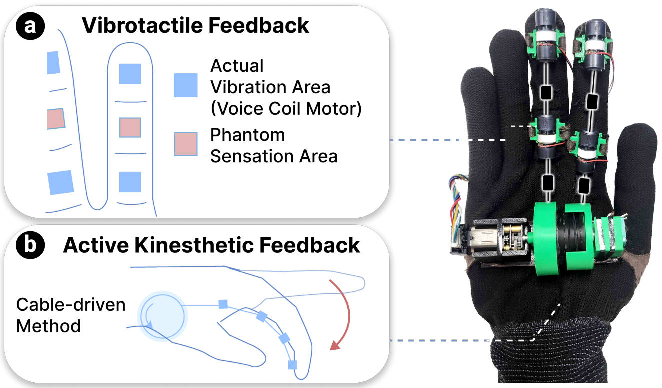

Fig. 2. System Overview. (a) We employed phantom sensation to implement spatiotemporal vibrotactile feedback. (b) We used a 1-DOF tendon-driven kinesthetic feedback to support shape perception.

have been developed to provide sensation on the finger area [28]–[30], no works have integrated this rendering algorithm with the kinesthetic feedback for 3D object shape perception.

In this paper, we propose a novel haptic rendering device that effectively enriches the sensation of grasping various shapes by delivering diverse vibration patterns across phalanges alongside low-DOF kinesthetic feedback (Figure 1). Prior research has not explored the differences in object shape recognition by reproducing the gradual tactile sensation from the proximal phalanx (PP) to the distal phalanx (DP) during hand flexion with the entire hand. Our method exploits the human perceptual system's ability to integrate proprioceptive information from hand movements with coordinated vibrotactile feedback [31] to create convincing illusions of different object shapes. We utilized funneling illusion [26], also known as the phantom sensation [27], which can generate stationary or moving patterns to modulate positional dimension. The experiments were conducted to find relationships with tactile patterns and the selection of the object shapes, and to evaluate user experience.

Our contributions are as follows:

- A novel haptic shape rendering approach that synchronizes multi-phalangeal spatiotemporal vibrotactile patterns with active kinesthetic feedback during hand flexion.
- An analysis of user studies validating shape perception tendencies across five haptic feedback conditions, with and without visual cues.

II. Implementation

We present a novel haptic rendering method and a haptic glove that delivers active kinesthetic haptic feedback while rendering vibrotactile patterns concurrently, as described in Figure 2.

A. Hardware

We use Arduino Leonardo as a microcontroller. A multiplexer (TCA9548A, Texas Instruments) and haptic motor drivers (DA7280, Renesas Electronics) are employed to operate voice coil motors for vibration. In addition, we used a micro metal gearmotor (#5227, Pololu) which generates 5.0 kg · cm of stall torque at 0.75 A and 12 VDC.

A right-hand glove is designed, incorporating four voice coil motors (TacHammer Drake HF, Titan Haptics) and a tendon-driven kinesthetic haptic module. The voice coil motors are attached to the PP and DP of the index and middle fingers. The same feedback was given to PPs or DPs of both fingers. We add holes to the glove at the locations of the vibration motors, and firmly fix actuators using velcro tape, allowing users to effectively perceive vibrations with their skin. A kinesthetic feedback module comprising a gear motor and a spool mechanism with a potentiometer is mounted at the center of the palm. The gear motor rotates the tendon-wound spool to facilitate hand flexion, and the spool is connected with a torsional spring to prevent tendon slack [10]. 3D-printed anchors on all phalanges route the tendon to guide desired hand movement, while the potentiometer tracks the degree of flexion. The required speed of 0.112 RPM is achieved through the PID controller.

B. Vibration Rendering Equation

The 1D stationary phantom sensation [32] and the 1D moving phantom sensation [33] algorithms were adopted to design our vibration patterns. We used the linear rendering method [34]. Intensity calibration was conducted for all participants to ensure perceptual consistency of the vibration amplitude with the proximal (A_{PP}) and distal (A_{DP}) phalanges due to differences in mechanoreceptor density [35], [36]. To establish a perceptual reference, the PP actuator was driven at its maximum intensity, denoted as A_{ref}. The intensity of the DP actuator was then calibrated to produce a perceived vibration that matched the reference. A perceptual compensation factor α was empirically determined such that the amplitude of the DP actuator was continuously scaled to match the perceived intensity of the PP actuator, according to the relationship $A_{\text{DP}} = \alpha A_{\text{PP}}$.

A stationary phantom sensation is generated by adjusting the relative amplitudes of two vibrotactile actuators on DP and PP phalanges, creating an interpolated tactile stimulus on the middle phalanges (IP). The vibration amplitude is calculated as Equation 1:

$$A_i = A_{\text{ref}} \left(1 - \frac{d_i}{D}\right) \tag{1}$$

where A_i is the amplitude of vibration, d_i is the distance from vibration motor i to the target location, and D is the total distance between actuators. The vibration duration is adjusted to control the duration of each stimulus to generate multiple tactile patterns.

For the 1D moving phantom sensation, a smooth transition of perceived vibration from the PP to the DP over time was created. The actuator amplitudes were defined by:

$$A_{\text{PP}}(t) = A_{\text{ref}} \left(1 - \frac{t}{T}\right), \;\; A_{\text{DP}}(t) = A_{\text{ref}} \left(\frac{t}{T}\right) \tag{2}$$

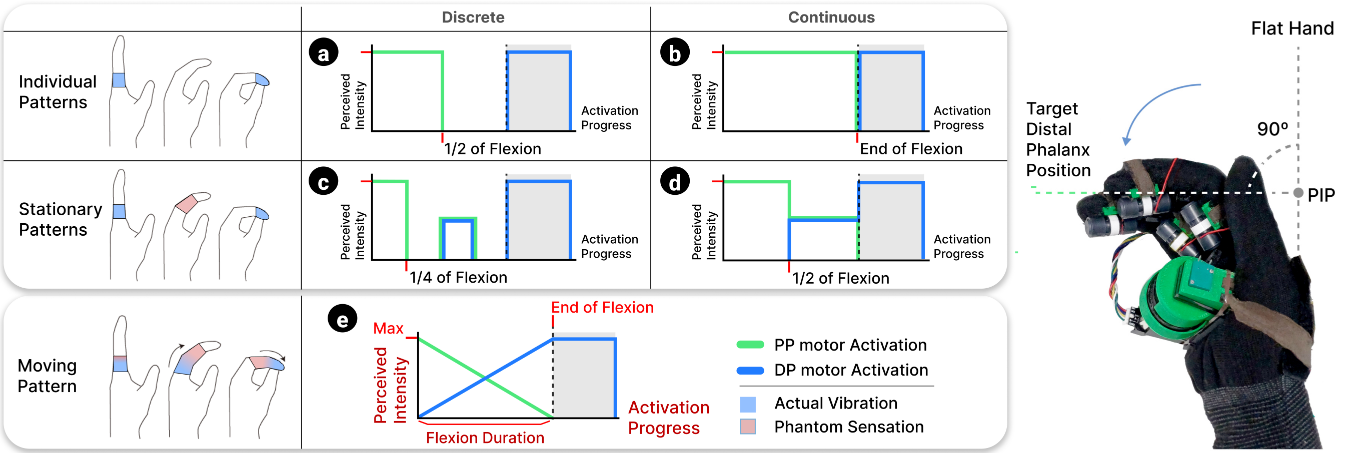

Fig. 3. Vibrotactile pattern design varying the positional dimension, including Individual activation, Stationary activation, and activation with Moving phantom sensation. We varied the temporal dimension by adjusting vibration duration, where 'Discrete' activates with a pause, while 'Continuous' keeps vibrating the previous actuated motor until the next motor activates.

where T is the total transition duration. To ensure perceptual consistency, the same intensity correction was applied only at $t = 0$, allowing the linear transition to proceed naturally.

C. Haptic Rendering Patterns Design

Before the experiment, we raised the following research question - *Will participants discriminate object shapes based on the vibrotactile stimulation, while the flexion progress and the final hand posture remain the same?* To address our research question, five vibrotactile patterns are designed for the experiment (Figure 3), which are provided along with kinesthetic feedback simultaneously during every activation. We aimed to provide a shape-like sensation mainly through the vibrotactile feedback. The role of kinesthetic feedback is to ensure that vibrotactile patterns are always delivered under the same flexion progress and joint angles per activation.

1) Active Kinesthetic Feedback Design: The active kinesthetic feedback, especially the flexion, is identically provided in every activation. The flexion is designed to start from a flat hand and end when the DP reaches the height of the flat hand's proximal interphalangeal joint (PIP). Before starting the experiment, we recorded each user's potentiometer value when the hand was flat and when the DP arrived at the target position. The motor is programmed to stop moving once it reaches the target potentiometer value.

2) Vibrotactile Feedback Design: Three primary vibration patterns were established based on the vibration area: individual point activation (Individual), activation with 1D stationary phantom sensation (Stationary), and activation with 1D moving phantom sensation (Moving). The Individual pattern activates the PP and DP separately. The Stationary pattern induces additional phantom sensations at the IP so that users can perceive distinct sensations in the PP, IP, and DP sequence. The Moving pattern creates a dynamic phantom sensation of simulating a shifting vibration from PP to DP [34]. Overall, the PP motor activates at the start of the flexion, while DP always vibrates for 0.5 s at the end of the flexion. The IP vibration triggers at the midpoint of the target potentiometer value. We provided sinusoidal vibration with a frequency of 120 Hz [17].

Next, we divided the Individual and Stationary patterns into Discrete and Continuous subcategories based on vibration continuity. Discrete patterns include pauses between vibrations, while Continuous patterns deliver individual vibrations to each phalanx sequentially without any break. To summarize, vibrotactile patterns including Individual-Discrete (I-Discrete), Individual-Continuous (I-Continuous), Stationary-Discrete (S-Discrete), Stationary-Continuous (S-Continuous), and Moving, were utilized in the studies. Along with the flexion, the vibration starts when the potentiometer reaches a certain value and lasts for a certain duration, which is shown in Figure 3.

III. Study 1: Shape Perception Study

The experiments aimed to investigate how vibrotactile patterns, along with kinesthetic feedback, influence participants' perception of object shapes. We analyzed the effect of vibration area and continuity on discriminating different forms. The study was approved by the Institutional Review Board (IRB).

The objective of Study 1 is to evaluate the correlation between the vibrotactile activation pattern and the object shape selection. We hypothesized that varying haptic patterns would influence shape perception and analyzed the tendencies for pattern selection. Additionally, we measured the vibration perception response rate for each phalanx to investigate its relationship with shape discrimination.

A. Design

A within-subject design experiment as described in Figure 4 was conducted, where participants experienced all five vibration patterns with kinesthetic feedback in a counterbalanced order and five repetitions, resulting in 25 trials per participant. They were given three object shape options - Cylinder, Octagonal Prism, and Quadrangular Prism - following the object provided in the research of power grasp taxonomy [37]. White

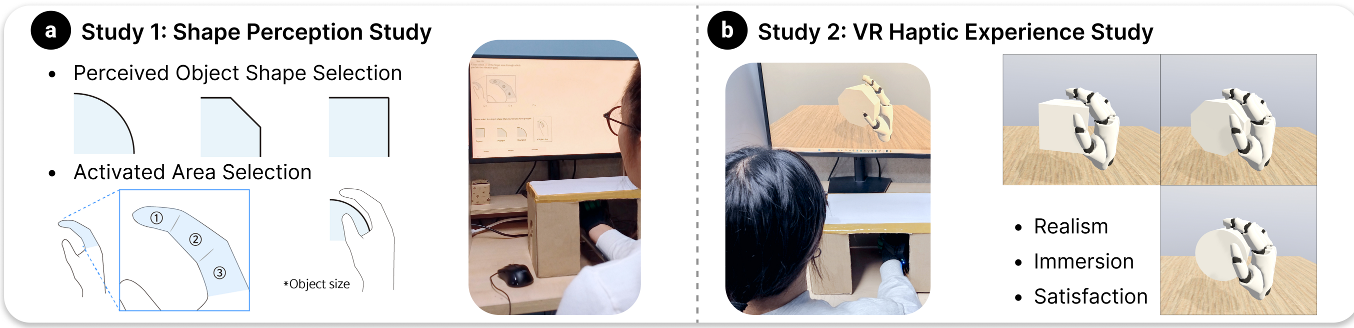

Fig. 4. Exemplary study setups. (a) Perceived shape and area activated by vibrotactile feedback and (b) Subjective ratings of haptic experience in VR.

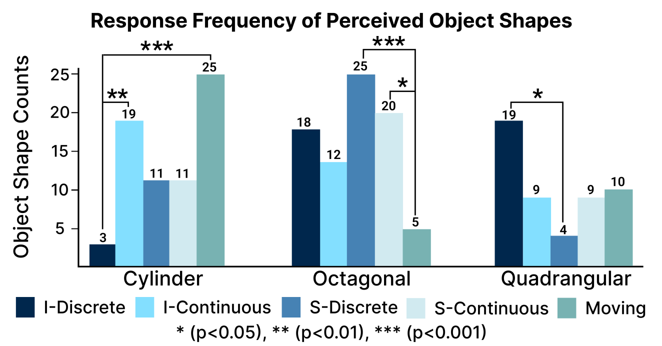

Fig. 5. The response frequency of five different haptic feedback renderings for associating three object shapes. The total number of trials for each pattern is 40.

noise and a box were provided to reduce visual and auditory bias.

B. Procedure

Ten right-handed participants (6 men, 4 women; Mean = 25.2 years old, SD = 3.22) were recruited. Before the experiment, we explained the study's purpose and calibrated the glove's kinesthetic and vibrotactile feedback. Kinesthetic feedback was adjusted by measuring potentiometer values during flexion until DPs reached the target position. Vibrotactile intensities were calibrated to ensure consistent perception between PP and DP. Participants then confirmed their ability to distinguish vibrations at PP, IP (phantom sensation), and DP. They were instructed to imagine grasping the object slowly, making contact from the right side to the top.

During the experiment, 20 main trials followed five training sessions, while the feedback was given with no repetition. We asked participants to close their eyes to concentrate solely on the haptic feedback. Participants answered the object shape they perceived during the grasp and indicated all phalanges where they felt vibrotactile activation. A post-study interview collected insights on shape selection criteria.

C. Result 1 : Object Shape Perception

We analyzed participants' shape selection behavior by performing a frequency analysis and conducting pairwise Chi-Square tests with Bonferroni-adjusted p-values. The graph of the frequency analysis result is shown in Figure 5. Several tendencies were found when selecting object shapes based on specific vibration patterns. S-Discrete ($p < 0.001$) and S-Continuous ($p < 0.05$) patterns showed a statistical significance in the selection of an Octagonal Prism over a Moving pattern. As for Cylinder, Moving ($p < 0.001$) and I-Continuous ($p < 0.01$) demonstrated a significantly higher selection tendency compared to I-Discrete. The preference for Quadrangular Prism remained notably higher in I-Discrete relative to S-Discrete ($p < 0.05$).

A chi-square test found a significant relationship between pattern type and shape selection ($\chi^2(2, N = 160) = 8.04$, $p = 0.0179$) as Figure 6 (a) describes. Fisher's exact test with Bonferroni correction revealed a significant difference ($p = 0.0225$) between Discrete and Continuous patterns for Cylinder grasping.

D. Result 2 : Activated Area Perception

We aimed to evaluate participants' perception of the activation location, as the area where the sensation was delivered varied depending on specific pattern groups. Pairwise Chi-square tests for proportions and Bonferroni corrections were conducted to examine differences in response frequency for each phalanx across the five feedback patterns. The result is described in Figure 6 (b). Among all patterns, only the I-Discrete pattern showed a significantly lower response rate in IP selection frequency compared to all other patterns (I-Continuous: $p = 0.0008$; S-Discrete: $p = 0.006$; S-Continuous: $p = 0.0008$; Moving: $p = 0.001$). In contrast, 85% of trials with I-Continuous patterns resulted in participants reporting a vibration on IP, despite the sensation being provided only on DP and PP.

IV. Study 2: VR Haptic Experience Study

In Study 2, our goal was to investigate the haptic experience of using our system while grasping virtual objects in VR. We evaluated the subjective ratings of five patterns while grasping three primitive shapes. Based on the results of Study 1, which revealed tendencies in object shape selection concerning specific patterns, we hypothesized that subjective rating scores would vary depending on the vibration pattern when grasping different object shapes.

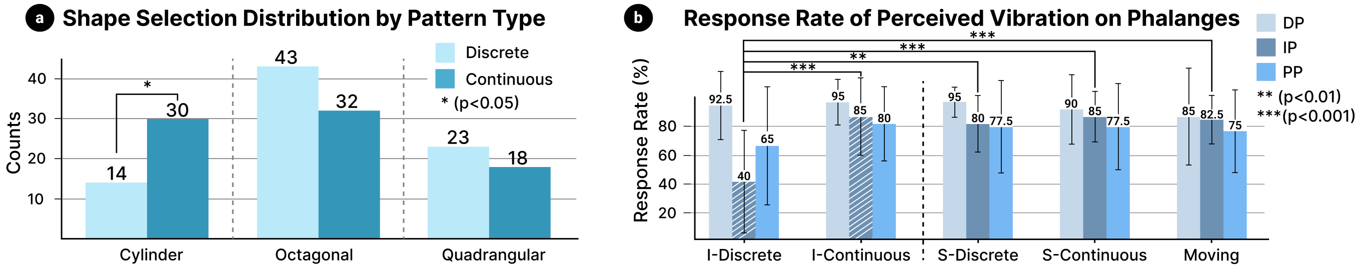

Fig. 6. (a) The comparison of shape selection between discrete and continuous patterns shows the relationship between pattern type and shape selection, (b) The response rate to perceived vibrations on the phalanges as induced by different vibrotactile patterns. Hatch patterns are applied to the bars representing *I-Discrete* and *I-Continuous* to emphasize that these are incorrect responses, as sensations are not provided to the IPs.

A. Design

A Unity scene was designed to display a hand grasping the same three objects used in Study 1, with five identical haptic patterns and kinesthetic feedback. The virtual hand position was fixed from wrist to palm to focus participants on the grasping sensation. Participants rated their VR haptic experience (realism, immersion, and satisfaction [38], [39]) for each pattern and object using a 7-point Likert scale. Regardless of the collision with virtual objects, the same five haptic patterns were delivered for all three object shapes.

B. Procedure

The same participants conducted the user study with a hand pose tracking module attached (Quantum Gloves, Manus Meta). They grasped virtual objects in the order of Cylinder, Octagonal Prism, and Quadrangular Prism in VR, experiencing all five haptic patterns for each object. After each pattern, participants rated their subjective experience, repeating sensations as much as needed. Once they felt confident in their ratings, participants moved to the next object. A brief interview was conducted afterward to gather feedback on their overall VR grasping experience.

C. Result

Based on the results of the Friedman test and Dunn's post-hoc test, we found several significant differences in participants' evaluations of realism, immersion, and satisfaction across different patterns and shapes (Figure 7).

For Cylinder-related experiences, the Friedman test indicated a significant difference across patterns for realism ($\chi^2(4) = 11.13$, $p = 0.025$) and satisfaction ($p = 0.02$). Post hoc analysis revealed that S-Continuous had significantly higher realism ($p = 0.014$) and satisfaction ratings than I-Discrete ($p = 0.017$). For Quadrangular experiences, the Friedman test resulted in a significant difference for realism ($p = 0.03$) and immersion ($p = 0.025$). Dunn's test showed that I-Discrete yielded higher ratings than S-Discrete in immersion ($p = 0.038$) and realism ($p = 0.027$).

V. Discussion

A. Shape Perception during Grasps

We investigated how different haptic feedback patterns influence shape perception during grasps and subjective ratings of haptic feedback in a VR environment. Study 1 results indicate significant shape selection tendencies based on vibration patterns. Stationary patterns were associated with the Octagonal Prism, while Moving and I-Continuous patterns led to Cylinder selection. The Quadrangular Prism was more frequently chosen with the I-Discrete pattern.

Interviews highlighted that four participants linked the absence of vibration at the IP phalanx to the Quadrangular Prism, while clear vibration at the IP phalanx was associated with the Octagonal Prism. Stationary patterns, which created a phantom sensation at the IP phalanx, consistently evoked the perception of touching the faceted surface of the Octagonal Prism, regardless of vibration duration. Additionally, eight participants identified continuous vibration moving across all phalanges as the primary cue for selecting the Cylinder, explaining the preference for the Moving pattern.

Study 2 revealed differences in realism, immersion, and satisfaction ratings across patterns and shapes. For the Cylinder, S-Continuous had significantly higher realism and satisfaction ratings than I-Discrete, while S-Discrete consistently scored low. This result indicates that Discrete patterns were unsuitable for curved surfaces. For the Quadrangular Prism, I-Discrete scored significantly higher than S-Discrete in realism and immersion, indicating that the individual activation at PP and DP is the key factor in creating a better grasping experience for the Quadrangular shape. On the other hand, the Octagonal Prism, exhibiting characteristics between the Quadrangular Prism and the Cylinder, requires a rounded hand shape while still providing distinct sensations of each angle while grasping. This feature may explain the lack of significant differences for the Octagonal Prism in contrast to the other shapes, which exhibited clear preferences for specific patterns.

B. Evaluation of Result Analysis

The response rate of the IP for the I-Continuous pattern was significantly high, despite no activation in that area. This result can be interpreted through the sensory integration model [40], which posits that human perception prioritizes sensory inputs based on their reliability. In addition, prior studies have shown that hand posture affects the perception of tactile stimuli [31], [41], supporting that tactile feedback perception is not absolute when integrated with proprioceptive information. I-Continuous was the only feedback activating the PP phalanx throughout

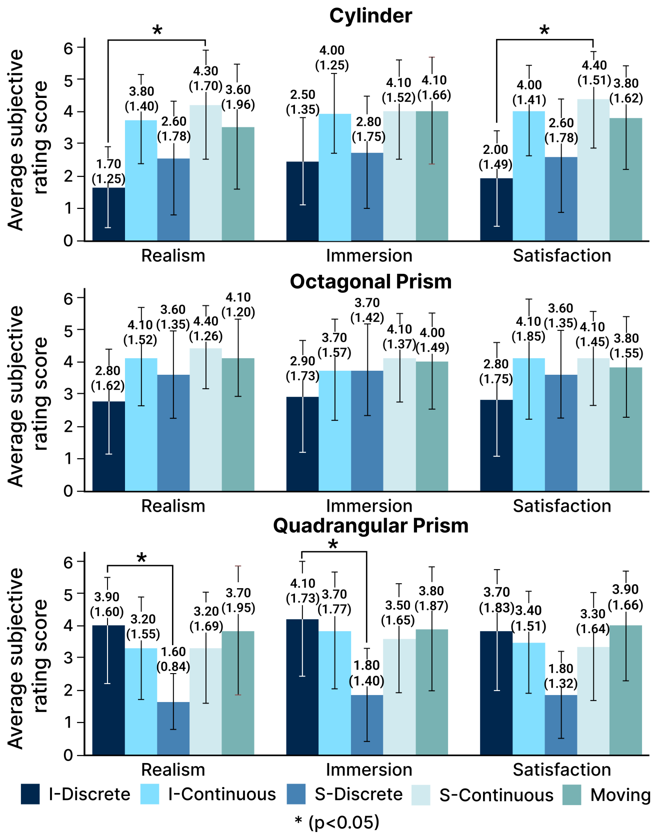

Fig. 7. Average ratings of object perception experience for five patterns applied to three shapes. These ratings reflect participants' subjective evaluations under three criteria: realism, immersion, and satisfaction.

the flexion. The dominance of consistent and reliable proprioceptive cues from kinesthetic feedback may have interfered with the less reliable and dynamic vibrotactile cues, potentially biasing the perceived location of the vibration to move toward the more flexed phalanx (IP - DP). This sensation transfer likely contributed to the preference for curved surfaces over right-angled shapes. Future studies should further investigate how the interaction between proprioception of hand movement and vibrotactile feedback affects the identification of stimulated locations. Also, future research on the phantom sensation algorithm regarding kinesthetic variables should proceed.

In Study 2, two participants found the pauses between activations in Discrete patterns unrealistic, which impaired immersion in VR. This aligns with the generally lower scores for Discrete patterns than Continuous patterns for Cylinder and Octagonal Prism. The observation contrasts with the results from Study 1, where participants preferred Discrete patterns for identifying the Octagonal Prism. Study 1 interviews with six participants also emphasized that Discrete patterns provided a clearer sensation of grasping angled objects than Continuous feedback, while no visual cue was provided. According to prior research, humans tend to perceive tactile cues more intensely when accompanied by visual cues [42], [43]. In Study 1, participants had to rely solely on haptic feedback to infer object shapes, requiring a clear and discernible sensation. However, in Study 2, visual cues reduced the need for explicit sensations to distinguish shapes, which likely led to higher ratings for the Continuous pattern.

C. Application

Three participants provided lower ratings when vibration feedback was perceived without corresponding virtual phalangeal contact with objects. They reported that the visual cue of hand-object interaction imposed stricter criteria for realism and immersion. These comments point out that in VR environments where explicit hand-object grasping is visible, predefined flexion of our haptic actuation has negatively influenced the haptic experience. To address this limitation, we propose utilizing our approach in scenarios with absent visual cues, such as environments with hand occlusion or restricted visibility. Furthermore, future research could explore the development of adaptive haptic systems capable of dynamically adjusting feedback rendering. Integrating our system with alternative rendering methods or collision-based passive haptic systems may enhance realism and improve user experience.

VI. Conclusion

We propose a novel haptic shape rendering method that enhances shape perception during grasping by combining spatiotemporal vibrotactile patterns created through the funneling illusion and varying vibration duration with low DOF kinesthetic flexion feedback. The User Study results indicate that participants tend to associate Continuous and Moving patterns with Cylindrical perceptions, while the Discrete patterns were perceived as angled shapes. In VR, Continuous patterns on Cylinders enhanced realism and satisfaction. Quadrangular shapes were better perceived with I-discrete patterns, while S-discrete patterns suited Octagonal shapes.

This study has a limitation in that our device has not been compared with conventional devices, so the enhanced performance relative to traditional methods has not been evaluated. Also, the fixed order of presented object shapes in Study 2 may have led to a biased result. Future work would include comparisons with other methods and the use of counterbalanced order for a more comprehensive assessment. Additionally, future research could explore expanding activation variables. Increasing the number of vibrated digits can be considered to examine how the number of vibration points affects the recognition of a wider variety of shapes. Also, future work could include the thumb for activation, as it also plays an essential role in recognizing object shapes and sizes [14]. By leveraging expanded activation variables, this work emphasizes the potential for better providing the sensation of diverse object shapes, thereby enhancing interaction in VR for industrial, educational, and entertainment applications.

Acknowledgment

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