석 사 학 위 논 문
Master's Thesis

가상 환경 내 사용자 동작 반영 햅틱 치환 알고리즘을 통한 자동 저작 시스템

In-situ Authoring with Posture-adaptive Haptic Rendering Algorithm for Virtual Reality

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In-situ Authoring with Posture-adaptive Haptic Rendering Algorithm for Virtual Reality

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Sang Ho Yoon
Professor of Graduate School of Culture Technology

The study was conducted in accordance with Code of Research Ethics[1].

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초 록

촉각을 재현하는 웨어러블 디바이스의 도래로 몰입감 높은 가상 현실 (VR) 속 경험이 가능해졌다. 그러나 촉각 경험을 구성하는 '햅틱 디자인 프로세스'의 확장성 및 자유도에 대한 논의는 다른 시각과 청각과 같은 감각들에 비해서 충분히 이루어지지 않은 편이다. 이에 맞서 본 논문에서는 가상 환경 내 즉각적인 햅틱 경험 설계를 가능케하는 저작 시스템을 제시한다. 햅틱 디자이너가 손에 햅틱 트레이스를 직접 그려서 진동 피드백을 작성할 수 있도록 함으로써 디자인 자유도를 확보하고, 사용자 친화적인 디자인 프로세스를 개발하여 저작 환경의 범위를 확장하고자 했다. 이를 위해 기존의 햅틱 치환 기법을 통합하여 손 전체에 적용하였으며, 다양한 손 동작 전반에 걸쳐 일관된 햅틱 피드백을 생성하는 '동작 반영 햅틱 치환 알고리즘'을 제안하였다. 나아가, 다수의 사용자 인지 실험을 통해 본 저작 시스템이 적용될 수 있는 사용자 시나리오를 시연하여 직관적이고 대응력이 뛰어난 시스템으로서의 가능성을 확인했다.

핵 심 낱 말 촉각 경험, 저작 도구, 햅틱 치환 기법, 웨어러블 디바이스, 가상 현실

Abstract

The emergence of vibrotactile feedback-embedded hand wearables enables immersive virtual reality (VR) experience. However, the haptic design process still lags behind its visual counterparts in terms of design freedom and scalability. In response, we present an in-situ haptic experience design for hand wearables in VR. Our system supports design freedom by allowing haptic designers to directly draw haptic traces on the hand to author vibrotactile feedback, requiring no controllers during the process. It enables a user-friendly and accessible haptic design process for VR hand interactions. We propose a new concept called phantom grid which enables a posture-adaptive haptic rendering algorithm that creates consistent haptic feedback throughout distinctive hand postures. Moreover, we incorporate multiple phantom sensation techniques to cover haptic feedback over the whole hand. We quantify the perceptual performance of our approach with multiple user studies with qualitative feedback. We also demonstrate applications showing how our method supports an intuitive, empowering, and responsive haptic authoring framework.

Keywords Haptic Experience, Authoring Tool, Haptic Rendering, Wearables, Virtual Reality

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Chapter 1. Introduction

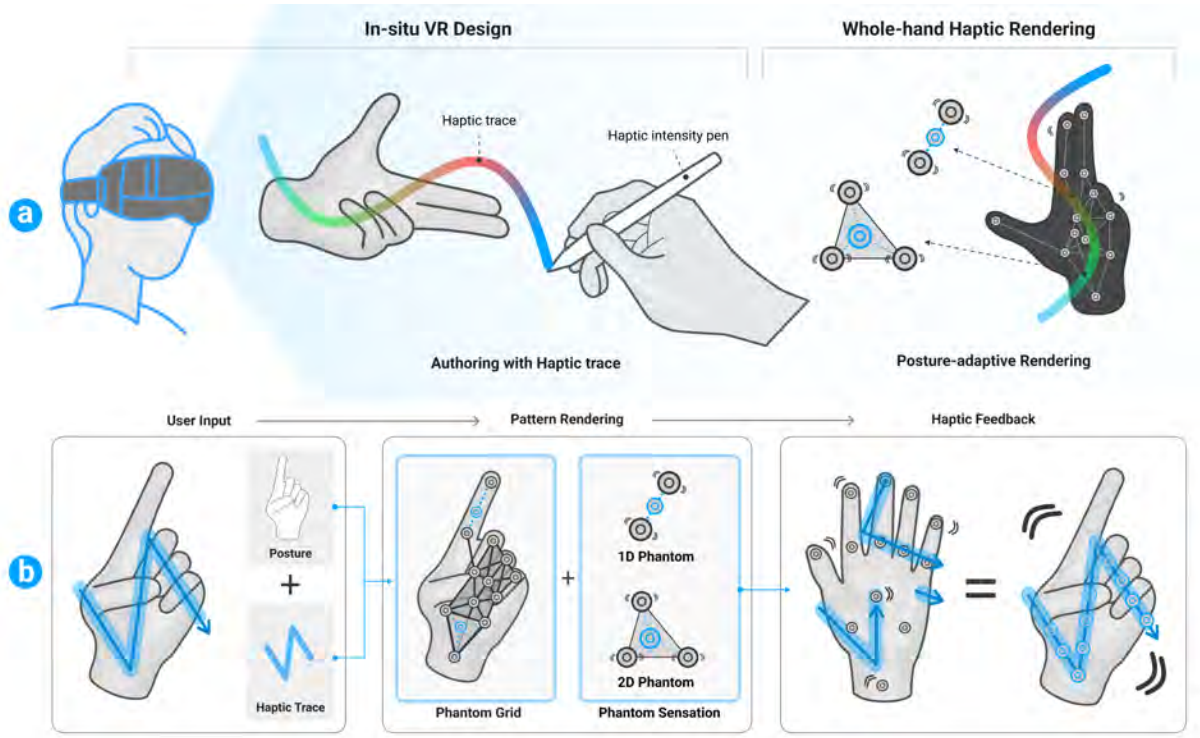

Figure 1.1: (a) An in-situ haptic authoring framework with a posture-adaptive algorithm to instantly translate haptic trace drawn in VR to whole-hand haptic feedback. (b) With given haptic traces, it maintains haptic experience over different hand postures using integrated 1D & 2D phantom sensation and a newly proposed phantom grid.

The advancement in graphics and audio technology offers immersive and realistic user experiences for virtual reality (VR). To further enhance the sense of embodiment [1], task performance [2], and immersiveness [3] in VR, incorporating haptic feedback in the forms of tactile and kinesthetic feedback showed promising results. Among various options, researchers came up with wearable tactile feedback devices [4, 5, 6] to provide effective stimulation while maintaining low-cost and small form factors. To support realistic tactile feedback, researchers put a high priority on simulating the sensation of hand touch [7, 8] since the hand is a key interaction medium between the user and the VR.

Researchers have utilized the hand for both interaction [9] and tactile sensation [10] with its high sensitivity and the frequency of its use in various applications. To provide an immersive and realistic experience in VR, tactile feedback is often delivered to the hand and forearm regions commonly utilized in touch interactions [11, 12, 13, 14]. To enhance wearability, previous studies employed gloves that incorporated vibration actuators to deliver vibrotactile feedback to the entire hand [15, 16, 17, 18]. These works supported limited spatiotemporal haptic experiences like providing discrete sensations over various locations of the hand. Recently, researchers demonstrated the performance of tactile rendering utilizing phantom sensation throughout a whole hand [19]. In our work, to support robust whole-hand tactile experiences under various hand postures, we strategically configure vibrotactile actuators by considering hand structure along with designated line (1D) and polygon (2D) based phantom sensations.

Previous haptic rendering approaches with the hand mainly focused on providing tactile sensation to achieve target goals [16, 12, 3, 20, 21, 22, 23] following physics-based interactions in VR. However, the perception of tactile sensation can easily alter based on the associated hand postures [24]. For example, even a small change in the hand configuration can easily affect a human's perceived sensation of vibrotactile feedback [25]. Despite advances in vibrotactile haptic rendering technology, current approaches still fall short in providing consistent and effective tactile sensations for different hand postures, requiring haptic designers to manually design different tactile feedback patterns for different hand postures to maintain similar haptic experiences. This is a huge drawback in VR since hand interactions recently have been gaining increasing attention with high expressiveness and control flexibility [26, 27]. To this end, we propose a hand posture-adaptive haptic rendering algorithm that automatically translates the given haptic design pattern to suit the associated hand postures. Our approach expedites the design process of vibrotactile feedback design by reducing the need for additional design iterations.

The haptic technology has the potential to contribute to the existing VR user experience by enhancing presence as well as effectiveness [28, 29]. However, designing haptic experiences is a highly complicated process since haptic experiences are multisensory and vertically integrated, where small modifications could affect the entire system's design [30]. This leads to considering various factors for haptic experiences, including "Design Parameters", "Usability Requirements", "Experiential Dimensions" and "Personalization Support" [31]. Based on these factors, recent works have demonstrated in-situ, instant, and customizable haptic design tools to enable users to compose intuitive and meaningful haptic experience design [32, 33]. Following the same path, we develop an in-situ and whole-hand vibrotactile feedback design tool for VR that acts as a copilot for users. We provide a user-friendly authoring environment by allowing users to freely draw the tactile feedback traces in the form of sketches on the hand with natural hand interactions.

In this work, we introduce a haptic design tool enabling hand posture-adaptive vibrotactile feedback design and rendering for VR hand interactions. To the best of our knowledge, no previous studies have suggested a haptic design tool that accommodated various hand postures when prototyping vibrotactile feedback for VR hand interactions. Our authoring framework supports instant playback and customization in VR to maximize the flexibility and quality of the haptic experience design process. We conduct user studies to validate the performance and system usability of our posture-adaptive haptic design tool, including perceptual tests and preference questionnaires. The overall results showed that our approach is empowering, intuitive, and responsive in prototyping vibrotactile feedback for VR hand interactions. Following is a list of our contributions:

- Vibrotactile actuators arrangement with line (1D) and polygon (2D) based phantom sensation considering the hand structure to enable whole-hand vibrotactile feedback;
- A novel concept called phantom grid enables a posture-adaptive haptic rendering algorithm that creates distinctive phantom sensations based on hand postures;
- A hand posture-adaptive haptic rendering algorithm capable of generating vibrotactile feedback patterns that feel similar on distinctive hand postures;
- An in-situ haptic authoring framework supporting instant playback and customization of vibrotactile feedback design for VR hand interactions; and
- Analysis of user studies and task evaluations for hand posture-adaptive haptic design.

Chapter 2. Related Works

In this section, we discuss previous design and rendering approaches to create haptic experiences for VR hand interactions. We review three key areas, including haptic interface for hand, tactile rendering with wearable haptics, and haptic design approaches in human-computer interaction (HCI).

2.1 Haptic Interface for Hand

Everyday experiences, from picking up a cup to typing on the keyboard, require the sense of touch to acquire tactile information to carry out a task [34]. Embedded with thousands of mechanoreceptors [35], hands are the primary receiver of haptic feedback among various body parts. Considering the wide range of tactile cue perception [7], researchers employ haptic feedback directly on the hand with various configurations to provide visual-tactile stimulation [8, 21], sense of penetration [36], and multimodal sensation [37, 38].

To transfer vibrotactile feedback to users' hands, handheld [39, 23], on-body [40, 41], and wearable [42, 43] form factors have been considered. Also, low-cost and small form factor commercial haptic gloves have been introduced [44, 45]. However, due to insufficient utilization of tactile illusions and heavy reliance on single-point vibrations, these gloves support tactile feedback to the hand with limited spatial coverage. To this end, researchers proposed whole-hand vibrotactile feedback with glove form factor [15, 16, 17, 18, 10] to provide direct hand stimulation and versatile interactive experiences. These works show improved spatiotemporal coverage and perceived performance for whole-hand tactile sensation. Still, previous works assume the static hand posture for rendering tactile sensation, which limits the feasibility and scalability. Hence, we propose proof-of-concept gloves consisting of 13 linear resonant actuators (LRAs). Based on our exploratory study, we set the location of actuators on the hand that helps maintain the tactile sensation for various hand postures.

2.2 Tactile Rendering with Wearable Haptics

Providing rich spatiotemporal vibrotactile feedback for hands, phantom sensation shows promising results in delivering effective performance with a limited number of actuators. Phantom sensation refers to the use of distant tactile stimulation to create spatial tactile illusion between two or more nodes [46]. This illusion allowed researchers to use less number of actuators to obtain equivalent spatial resolution achieved with a larger number of actuators. Previous works validated the performance of phantom sensations across different body parts [47] including head [48], arm [49], torso [36], back [50], and wrist [51, 52]. These works utilize phantom sensation to support navigation tasks [53] and motion guidance [54]. In our work, we integrate line (1D) & polygon (2D) based phantom sensations [55, 56] to render continuous vibrotactile feedback across the whole hand.

Researchers have employed phantom sensation in hands since hands have high tactile sensitivity, flexibility for diverse wearable form factors, and potential for rich sensory experiences [57]. Previous works deployed phantom sensation in wearable [58] and hand-held [22] form factors to deliver within- and out-of-body [17, 59, 60] tactile sensations. Also, researchers succeeded in rich tactile sensation on the palm and the whole hand using a sparse 2D array [61] and merging 1D & 2D phantom sensations [19].

Still, previous works assume static hand posture where the designed phantom sensations could be fragile upon the user's hand posture changes.

Previous works on human perception reported that a small change in hand posture easily causes confusion in tactile direction and distance [24, 25]. Here, we see that the geometric configuration of the hand plays an important role in determining perceived sensation. Also, this tells the significance of considering hand postures for VR hand interactions since they are often dynamic and diverse in nature. For our work, we propose a posture-adaptive phantom grid with associated rendering methods that modify 1D & 2D phantom sensation regions and motor parameters according to given hand postures.

2.3 Haptic Design in HCI

With the rise of multisensory interactions in HCI, researchers suggest a theoretical model of factors for understanding and evaluating haptic experience [31]. Still, there are many challenges to the haptic design process [62]. Researchers found that the current haptic design needs real-time feedback and direct modification on demand for a better designing experience [31, 62]. In addition, perception on any given haptic design is individual [63] and context dependent [64]. Looking at the previous pain points, a haptic design framework should support an instant design iterations [30] and cope with a haptic hardware platform for on-demand design modification [65].

To support an interactive haptic design process, recent works showcase a responsive web-based authoring interface [66], trace-based vibrotactile feedback design [44], and sketching on 3D body [67]. These methods support instant haptic feedback and fine-tuning control panel, allowing quick design iterations. For example, bHaptics Designer allows users to play and feel the designed vibrotactile effects directly. However, a 2D desktop GUI-based toolkit makes it hard to achieve in-situ haptic design modifications for VR hand interactions since users need to switch between the desktop and VR interface to design a haptic effect. Recent works suggest in-situ prototyping for a VR environment with direct manipulation [68] and vocalization [32]. Inspired by these works, we propose an in-situ VR haptic design tool where users directly design vibrotactile feedback patterns on hand solely based on hand interactions.

Researchers showed that users prefer more freedom and control over fixed preset patterns for designing haptic effects [69]. To this point, previous works offered tactile animation authoring tools which allowed users to directly manipulate phantom tactile sensation location [70] or paint strokes on a virtual model for tactile pattern [71]. We extend from previous works where we allow users to directly draw a trace on one's own hand to design vibrotactile feedback patterns. Unlike previous third-person perspective design tools, we offer a first-person perspective haptic design experience to induce an accurate interaction to design vibrotactile feedback on hand [72]. Moreover, we entitle instant playback and customization to our design tool to fulfill the existing pain points in haptic experience design.

Chapter 3. Design of In-situ Haptic Authoring Framework

In this section, we report the development and design details of implementation, a posture-adaptive haptic design toolkit that alleviates the mental and physical load of haptic designers (Figure 1.1).

We carried out an exploratory study to understand the effect and performance of vibrotactile feedback with various hand postures. Moreover, we conducted a small pilot study with novice hapticians [62] to determine the limitations and requirements for an in-situ haptic design tool for VR hand interactions. For our initial analysis, we directly attached 12 LRA motors (VG1040003D, Vybronics) operated with motor drivers (DA7280, Dialog Semiconductor), as shown in Figure 3.1a, which cover most areas on the palmar side of the hand. We used adhesive tape (468MP, 3M) to attach electrical components to the skin throughout the analysis.

3.1 Haptic Performance on Hand Postures

We conducted an exploratory study on tactile feedback performance under various hand postures. We investigated how various hand postures impact physical and psychophysical performance for the whole-hand vibrotactile feedback. In terms of physical performance, we collected spatiotemporal accelerometer measurements of skin vibrations for a given vibrotactile feedback on various hand postures. For the psychophysical study, we measured the information transfer (IT) in bits [73] to confirm the information transmission capacity change upon hand postures. We picked five commonly used hand postures in VR [74, 75, 76, 77] including *Rest*, *Finger Gun*, *Thumbs Up*, *Fist*, and *Pointing* (Figure 3.1b). Also, we put stimulus tactors on the non-dominant hand (left-hand) since the non-dominant hand tends to be more sensitive to somatosensory feedback [78, 79]. Throughout the study, we aim to verify the physical and psychophysical distortions in given vibrotactile feedback.

3.1.1 Exploratory Study 1: Spatial Distribution of Whole-hand Skin Vibrations

For physical performance, we examine the propagation of skin vibrations throughout the hand. While the qualitative aspect of human sensation is important, it is also necessary to quantitatively confirm how vibrotactile actuation spreads throughout the skin [80].

Setup We recruited 10 participants (4 females, 6 males) with a mean age of 22.9 who were right-handed. We attached 13 accelerometers (ADXL335, Analog Devices) along with LRA motors (VG1040003D, Vybronics) (Figure 3.1a). For each motor driven with an input voltage of 2.5 Vrms and a frequency of 170Hz, the vibrations (in m/s^2) were measured from 13 accelerometers. Vibration intensity was measured with the root mean square (RMS) value of the data acquired for 1.5 seconds at a sampling rate of 4.4 kHz. We repeated this for all five hand postures to collect a total of 23,400 data points (10 participants×5 hand postures×12 motors×13 sensors×3 trials). From the RMS values of acceleration, we obtained a skin vibration heatmap for the whole hand, similar to [81].

Result We observed an increase in the spreading area and amplitude of skin vibrations as the hand posture involved more skin contact. The points of skin contact serve as extra pathways for vibration propagation (Figure 3.1d). Figure 3.1c utilizes skin vibration heatmaps to illustrate the distribution of skin vibrations on different hand postures. We noticed that the posture with a high occurrence of skin contact has a tendency to widespread skin vibrations. Here, the skin contact area increases in the order of *Rest*, *Finger Gun*, *Pointing*, *Thumbs Up*, and *Fist* postures.

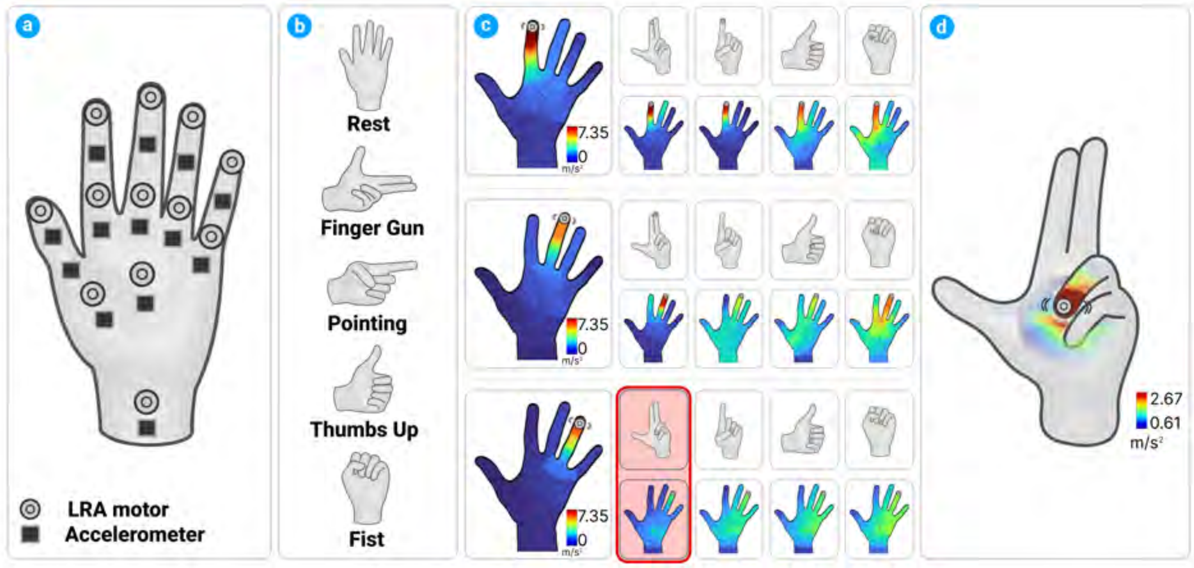

Figure 3.1: We measured vibrations from (a) 12 hand regions using 13 accelerometers on (b) five hand postures. (c) Interpolating accelerometer measurements produces heatmaps showing the distribution of motor-elicited skin vibrations. (d) An example of skin vibration propagation from the finger to the palm.

3.1.2 Exploratory Study 2: Information Transfer

For psychophysical performance, we examine the baseline performance of multi-tactor haptic system on hand by measuring information transfer capacity under a condition where no further rendering method like phantom sensation was used. Moreover, the results confirmed that hand postures affect users' psychophysical performance on vibrotactile feedback.

Setup We recruited another 10 participants (6 females, 4 males) with a mean age of 23.0 who were all right-handed. We used the same hardware setup as the previous study, excluding accelerometers. To prevent getting any auditory or visual clues, participants wore a noise-canceling headset that played white noise and their left arm was separated by the display monitor. To measure IT, we activated 12 motors one at a time for three seconds in random order and repeated this for all five hand postures. After a stimulus was played, we asked participants to choose the location where they felt vibration. Participants responded using a mouse click with a given GUI showing the 12 motor locations. A total of 46,800 data points were collected (10 participants $\times$ 6 trials$\times$12 motors$\times$5 hand postures$\times$13 sensors). To minimize fatigue, a 5-minute break was given after every 3 trials along with extra breaks upon request.

Results Figure 3.2 shows how IT varies depending on the hand posture. Non-*Rest* hand postures exhibit relatively low IT. Among them, the *Fist* posture, which had the most skin contact between the fingers and the palm exhibited the lowest IT (2.10 bits). This signifies that the widespread vibration propagation negatively affects the user's vibrotactile perception. In order to prevent these problems, haptic designers should create haptic designs with the corresponding postures in mind. This would subsequently increase design task loads since the designers need to compute the distortion of motor vibration upon skin contact constantly.

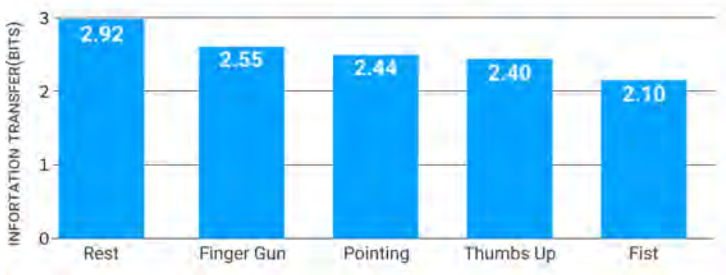

Figure 3.2: Information transfer (IT) for different hand postures. All hand postures showed a decrease in IT compared to the *Rest* posture. IT decreases more as the number of finger flexion increases.

3.2 Pilot Study on Early Prototype

We enhance the design of our toolkit by assessing the proof-of-concept toolkit. Here, we implemented primary features for conventional in-situ haptic design tools including hand tracking-based haptic design, instant customization in VR, and hand posture-adaptive compensation using skin vibration heatmaps.

Setup & Procedure We recruited 12 novice hapticians (7 females, 5 males) with a mean age of 23.3 who were all right-handed. Participants were equipped with a VR headset (Oculus Quest Pro) and 12 LRA motors (Figure 3.1a). First, we had a five-minute practice session to explain the user interface and associated functions. Then, we asked participants to design vibrotactile feedback to match the given visual effects (VFX) for six VR hand interactions (blasting, gun shooting, electric shock, magic wand, explosion, and energy ball) on five different hand postures (Figure 3.1b). We encouraged an iterative design process without a time limit to collect in-depth feedback from participants. After the entire design process was over, we obtained qualitative feedback from participants on the overall design experience as well as the vibrotactile feedback itself. The study took about one hour for each participant.

To support in-situ haptic design, we provided an interface where participants could edit and play the designed vibrotactile feedback instantly inside the VR environment. The participants evaluated two distinct toolkits, each of which employed a different rendering approach. In the first approach (manual design), users had to manually select the motors on their virtual left hand to create a vibrotactile sequence over time. They were given a corresponding skin vibration heatmap for haptic design assistance when they hovered around the motor region. On the other approach (automated design), participants designed by coloring their left hand to designate the target stimulation area over time. Based on the colored region, the system determines which motor to activate in consideration of the skin vibration heatmaps so that the colored region stimulates prominently.

Pilot Study Feedback As expected, participants gave positive comments on the in-situ design in VR, as it was shown in [32]. However, participants sought more detailed customization features such as control over vibrotactile intensities and sequences, or the ability to edit the vibrotactile feedback in time series. In terms of the rendering method, all participants preferred the automated design approach, which gave designers fewer tasks and allowed them to rely more on the system. *"I felt much-reduced task load since I did not have to care about which motor to activate. (P10)"*. In the same context, participants barely utilized the provided heatmaps for the manual design approach since it increased task complexity. Also, we discovered a drawback of a hand-tracking-based tool due to frequent errors when the hands overlap in the field of view. Besides, the design of some participants exceeded the working space of our vibrotactile glove, causing a perceptual discrepancy. Lastly, participants reported a gap between perceived sensation and their design. *"It would feel much better if more tactors are attached on different hand regions. (P7)"*.

3.3 Results and Findings

Based on the findings of exploratory and pilot studies, we structured considerations for designing an in-situ haptic design tool for VR hand interactions. By setting the cornerstone with learned lessons, we define a design space for the proposed haptic authoring framework.

Detailed customization support for in-situ VR authoring With the advancement of the VR authoring environment, recent works have shown improved performance and benefits using in-situ VR haptic design process [32] over conventional desktop GUI approach [44]. Aligned with the previous study, we also received positive feedback from participants. *"It is intuitive to design haptic feedback directly on the hand while watching VFXs in VR. (P8)"*. Furthermore, we also discovered users' demand for more detailed spatiotemporal customization of the vibrotactile feedback design. To be more specific, participants prefer to control the intensity of the vibrotactile feedback and preview the designed pattern with a visual aid such as animated traces.

Balancing between design freedom and system robustness Designing a haptic experience is a complicated task where spatial and temporal elements should be considered simultaneously. With numerous vibrotactile stimuli, the design task gets complicated and restricts haptic designers from creating rich and complex sensations. To support similar design freedom as the previous work [71], our system allowed users to color the virtual hand using natural hands. Unlike previous works, we do not require controllers as all interactions are done based on hand tracking. Participants showed positive feedback on utilizing the concept of sketching. *"It was convenient to design haptic feedback through coloring with natural hands compared to selecting and adjusting motors. (P4)"*. Several participants, however, also showed concerns about the system's robustness related to hand tracking. As P2 mentioned *"VR hand tracking seems fragile when two hands are in contact or crossing each other."*, participants prefer animated traces to represent the spatiotemporal aspect of the haptic design. Therefore, the proposed system and interface should provide a hand-tracking-based tracing interaction with improved robustness.

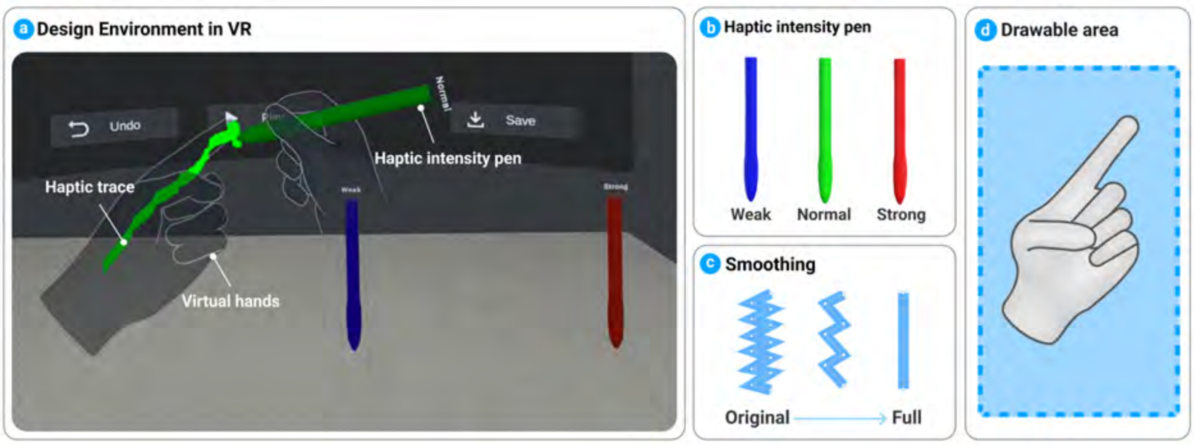

Figure 3.3: (a) A user sketches haptic trace with a (b) haptic intensity pen on the virtual hand. Upon user sketches, the system collects trace data points at 100 Hz which can be used for (c) smoothing haptic traces if needed. (d) A drawable area refers to the region around the hand to draw haptic traces.

Automated and adaptive haptic rendering for hand postures During the pilot study, participants reported hardship in designing vibrotactile feedback with various hand postures in mind. For different hand postures, designers must maintain spatial relationships while preventing unexpected vibration propagation due to skin contact. Although the system provided supplementary information (*e.g.*, skin vibration heatmap) for design guidelines, participants still reported a high task load since it was hard to connect provided information for the haptic design. *"I had no idea how to utilize the given skin vibration heatmap for the haptic design.(P12)"*. Also, participants reported fatigue in the overall design process since they had to iterate the same design process from scratch for each hand posture. To resolve these issues, the proposed design toolkit should be embedded with a posture-adaptive backend haptic design algorithm. This would allow an automated design process across various hand postures and reduce the workload of haptic designers.

3.4 Overview of Interface

We develop the framework considering the design space defined from exploratory and pilot studies. We propose an in-situ VR authoring framework that 1) aims at high design freedom and detailed customization support, 2) maintains system and interaction robustness, and 3) incorporates an underlying automated algorithm for posture-adaptive haptic rendering.

Our framework was developed with C# using the Unity3D Engine (2021.3.6f1). We employed Oculus Meta Quest Pro HMD where we utilized the Unity-Oculus integration plugin. Figure 3.3 illustrates the user interface. To facilitate a controller-less design environment, we adopted Oculus Interaction SDK to support basic hand tracking and interactions such as raycasting & pinch-based pointer pose. To avoid hand tracking loss when drawing the vibrotactile traces on the hand directly with a finger due to hand overlapping issues, we came up with the concept of virtual haptic intensity pens (Figure 3.3b). Employing a haptic intensity pen in VR as a tool to draw haptic traces on the hand improved the robustness of hand interaction since this method naturally maintains a certain distance between the user's hands which in turn reduces hand tracking errors. We also provided multiple colored pens to represent different vibrotactile intensities (blue-weak, green-normal, red-strong).

When users initiate sketching with the haptic intensity pen on the virtual hand, our system collects sketching points at 100 Hz to form haptic traces. As shown in Figure 3.3c, the system keeps traces smooth after each stroke. The smoothing is done by taking sketching points at every constant interval which is determined by how smooth the user wants the trace to be. Our tool provides features for detailed customization support such as 'Undo haptic traces', 'Instant haptic playback', 'Edit pattern', and 'Save'. Furthermore, we embed the underlying posture-adaptive algorithm (See **Section 3.6**) in this tool, so users do not need to carry out any extra tasks to experience the same haptic design in various hand postures. If users change hand postures, the system automatically modifies designed haptic traces.

System Walk-through We explain a step-by-step procedure for our authoring framework. First, the designer chooses a posture to start the haptic design process. Then, the virtual hand gets fixed to the selected hand posture for users to sketch. We supported five hand postures including *Rest*, *Finger Gun*, *Thumbs Up*, *Fist*, and *Pointing*. The designer can sketch multiple independent traces that can be spatially overlapped, but to keep haptic rendering precision, they cannot be actuated simultaneously. The system supports an instant playback feature where haptic traces are animated on an empty virtual hand (Figure 3.3a∼c). The animated haptic traces are synced with actual hardware, so designers can easily experience designed vibrotactile feedback in-situ. Lastly, the haptic design can be saved by selecting the save button, which automatically generates vibrotactile patterns for different hand postures by applying our posture-adaptive algorithm to the created design.

Drawable Area In the early prototype pilot study (See **Section 3.2**), we noticed that participants often drew continuous traces between the inside and outside of their hands. For instance, participants continued traces outside the hand region. To provide more design freedom for users, we set the boundary of the canvas to span beyond the hand (Figure 3.3d).

Once the haptic pattern is designed for a single posture, the system automatically translates the vibrotactile patterns for other hand postures (See **Section 3.6**). By selecting different hand postures from the UI panel, the designers can experience automatically modified haptic design. Furthermore, designers can also edit the haptic design for each posture if needed. When designers are satisfied with the haptic design, the submit button stores vibrotactile patterns for all hand postures.

3.5 Hardware

We built wearable haptic gloves to work with our authoring tool as shown in Figure 3.4. We decided to design our own haptic glove that creates rich sensations but does not impair users' movement. As a result, we designed a haptic glove constituting 13 motors, illustrated in Figure 3.4a. To decide the number of motors, we first looked into the required spacing distance between motors. For a clear haptic transmission, the motors should be close enough to create a phantom sensation, but at the same time far enough so that they won't disturb each other and cause any discomfort during hand movements. Considering the above factors and referring to existing literature [61, 82], we positioned the motors more than 15 mm away from each other.

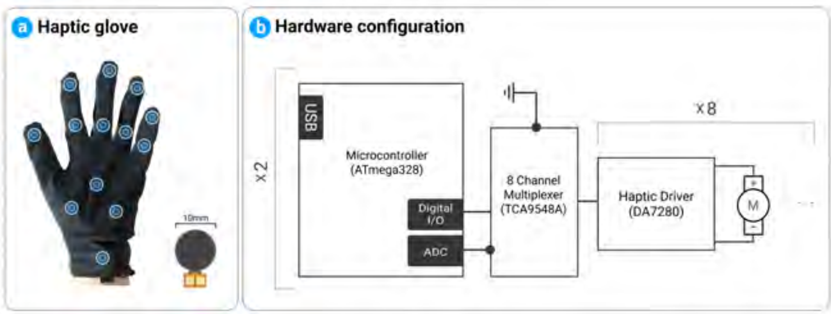

Figure 3.4: Schematic view of our (a) proof-of-concept haptic glove embedded with 13 LRAs and (b) its hardware configuration.

Our glove is made with conventional fabric for sports gloves (polyester 85%, polyurethane 15%) and is available in two different sizes (M/L & L/XL). 13 LRA motors (Vybronics; resonant frequency: 170 Hz; rated voltage: 2.5 Vrms; size: 10 $\times$ 4mm) are attached inside of the glove using double-sided adhesive (3M, 468MP)). We operate two Sparkfun Redboards (16 MHz Atmega328) with 8-to-1 multiplexers (TCA9548A, Texas Instrument) to control a total of 13 haptic drivers (DA7280, Dialogue) and 13 LRA motors 3.4b. We kept enough length ($\geq$30 cm) for interconnecting wires to maintain robust connections during hand movements. The latency from command to actuation trigger was less than 4 ms and the maximum frame rate was 250 Hz. The development and user studies operated using a desktop PC with a 3.2 GHz Intel Core i9 processor.

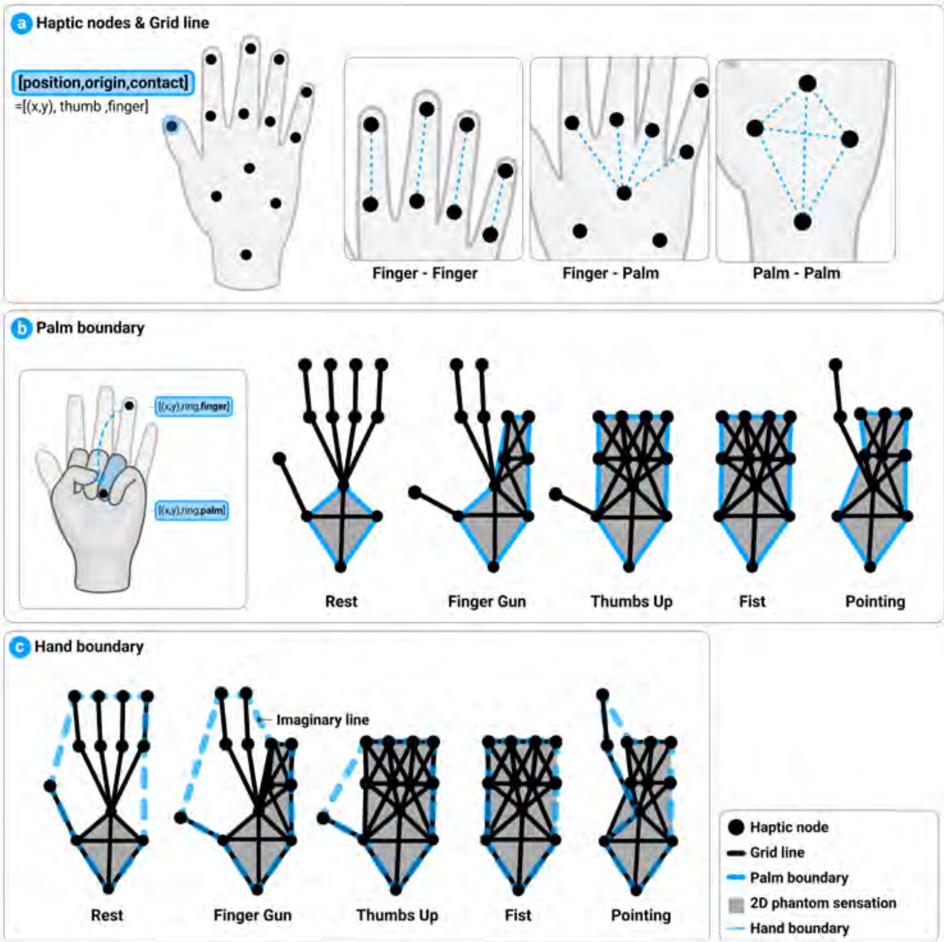

Figure 3.5: (a) A haptic node contains (x,y) *position*, *origin*, and *contact*. Connecting adjacent haptic nodes on the finger and the palm form grid lines. (b) We form palm boundary utilizing the haptic nodes on the palm which expands if the finger is folded for different hand postures. (c) The hand boundary is set to encompass the outermost grid lines and extra imaginary lines are used to complete the closed hull.

3.6 Posture-adaptive Algorithm

In this section, we explain our underlying algorithm to support various hand postures. First, we describe a new haptic rendering plane called phantom grid which formulates different phantom sensation relationships according to various hand postures. Next, we explain how we integrated 1D & 2D phantom sensations along with the phantom grid. Lastly, we show different rendering methods in accordance with the phantom grid to support similar vibrotactile sensations over different hand postures.

3.6.1 Phantom Grid Construction

The phantom grid is a basis for haptic rendering consisting of nodes and edges that incorporate the spatial information of the whole hand. The main role of the phantom grid is to create a haptic rendering map where we can employ 1D & 2D phantom sensations on. Figure 3.5 showcases the major components for phantom grid construction. Phantom grid construction starts by identifying the details of haptic nodes that represent the location of 13 LRAs on the hand.

Haptic Node A haptic node (Figure 3.5a) is a reference point for the phantom grid construction.

Each LRA attached to the haptic glove becomes a haptic node. The haptic node consists of three variables including *position*, *origin*, and *contact*. The *position* refers to the x and y coordinates of the LRA motor's location which varies among hand postures. The *origin* represents the original attached locations of the LRA motors (*e.g.*, thumb, index, middle, ring, little, palm), and *contact* tells which body area the haptic node contacts with (*e.g.*, finger, palm). Here, *contact* variable may change depending on the finger flexion conditions in different hand postures. For example, the haptic node located on the ring fingertip moves closer to the palm center node than the node located on the proximal phalanx for *Fist* gesture. Then, this changes the *contact* variable from 'finger' to 'palm' as shown in Figure 3.5b.

Grid Line Grid lines (Figure 3.5a) are edges connecting two haptic nodes that create a phantom sensation. Two adjacent nodes create a phantom sensation when their *origin* or the *contact* is the same. A grid line is established between any two adjacent nodes that are close enough to allow skin vibrations to propagate from one to the other. Within a finger, a 1D phantom sensation can be generated using 2 motors. 2 motors were enough to cover the entire finger, and for ease of movement. We attached motors on both ends (distal phalange and proximal phalange) of the fingers except the thumb, which does not have a middle phalange. By putting 4 motors on the palm area, we create a 1D phantom sensation connecting the motors attached to the finger and palm if the motors are close enough. Not only 1D phantom sensation between 2 motors but also a 2D phantom sensation is available with the motors located on the palm.

Palm Boundary A palm boundary (Figure 3.5b) designates the region for 2D phantom sensation. By default, four haptic nodes at the palm form the palm boundary. This boundary expands if a finger is folded as shown in Figure 3.5b. Upon finger flexion, fingertip nodes come into contact with the palm, which causes motor-elicited skin vibrations to spread throughout the palm and contact fingers. All these nodes are then considered to be on the palm and utilized for producing a 2D phantom sensation. The palm boundaries for all hand postures are illustrated in Figure 3.5b. Each boundary encompasses finger haptic nodes that make contact with the palm.

Hand Boundary We define a hand boundary (Figure 3.5c) to render the haptic sensation outside the palm boundary. Like the palm boundary, we obtain the concave hull of all the nodes on the hand, which gives different boundaries per hand posture. In contrast to the palm boundary, a hand boundary cannot be made using only the grid lines, so we create imaginary lines (Figure 3.5c) to complete the concave hull. In cases when a point is mapped to an imaginary line, the nearest motor is activated for rendering.

3.6.2 Integrated 1D & 2D Phantom Sensation for Whole Hand

We integrated previous phantom tactile sensation algorithms [61, 50] to enable continuous vibrotactile feedback covering whole hand. Here, we employed both 1D & 2D phantom sensation techniques to respond to all possible areas covered by the phantom grid. A phantom sensation for a target location is created by stimulating three nearby motors (2 motors for 1D & 3 motors for 2D cases). Three different models (linear, logarithmic, and energy) were previously proposed to adjust the amplitude of each motor. Among those, we chose the energy model shown in Eq. 3.1 [61] which demonstrated the best phantom localization accuracy compared to other models [50, 70].

$$A_{motor} = \sqrt{\frac{1d_{motor}}{\sum_i 1d_i}} A_{target} \text{ (A: amplitude, d: distance from a motor to the haptic point)} \tag{3.1}$$

3.6.3 Posture-adaptive Haptic Rendering

With the proposed phantom grid and phantom sensation approaches, our tool enables haptic rendering for various hand postures. The users design vibrotactile patterns in the form of 2D traces, which we call haptic traces. These traces consist of points collected at 100 Hz, which we call haptic points. We execute various haptic rendering methods according to the geometric relationship between the haptic point and the phantom grid. The geometric relationship includes haptic node collision, grid line intersection, within-palm localization, and outside-palm localization. Haptic node collision, grid line intersection, and within-palm localization can be rendered directly using the 1D & 2D phantom sensations. However, outside-palm localization requires an extra translation phase, the nearest point mapping for the haptic rendering.

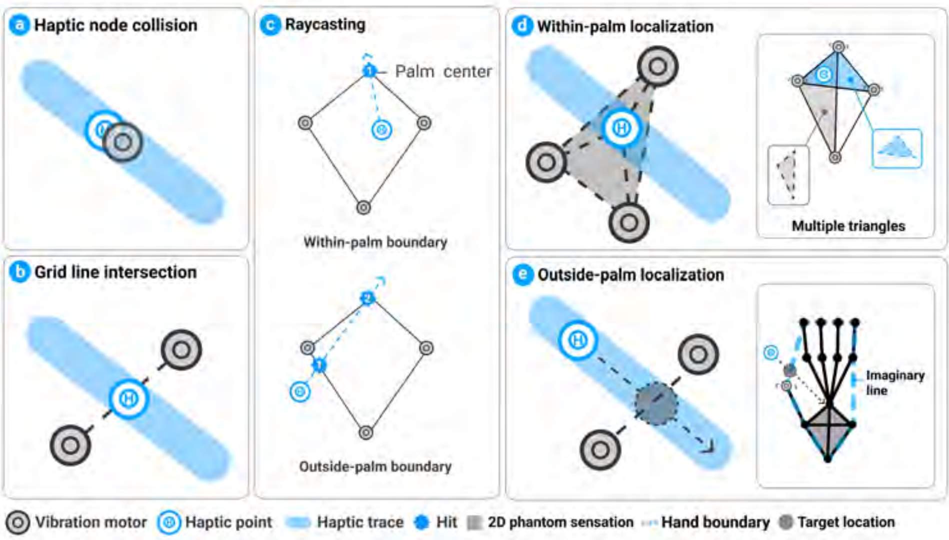

Figure 3.6: (a) Haptic node collision activates the motor with which the haptic point overlaps. (b) Grid line intersection uses 1D phantom sensation between two haptic nodes of the grid line. (c) Raycasting algorithm determines whether a haptic point is within or outside the palm. (d) Within-palm localization uses 2D phantom sensation using three haptic nodes forming the enclosing triangle. With independent modulation of tactors, we proceed with the first triangle found. (e) Outside-palm localization projects the haptic point to the nearest hand boundary.

Haptic Node Collision This is the simplest form of haptic rendering. We loop through all haptic nodes and compute the distance between each haptic node and the haptic point. If the point lies within the distance threshold (physical motor size), the system activates the corresponding motor with the target amplitude (Figure 3.6a).

Grid Line Intersection If the haptic point locates on the grid line, we employ 1D phantom sensation. Since a grid line is created by connecting two haptic nodes, we drive these motors with Eq. 3.1. The amplitudes of the motors are adjusted based on the position of the haptic point within the grid line (Figure 3.6b).

Raycasting Algorithm If a haptic point belongs to none of the above, the haptic point would be located either inside or outside of the palm area polygon created by the palm boundary (Figure 3.6c). We use the raycasting algorithm (Figure 3.6c) to distinguish between these two. Suppose the number of intersections between the palm boundary and a ray from the haptic point towards the palm center is odd.

In that case, the haptic point locates within the palm boundary (Figure 3.6d) and vice versa (Figure 3.6e).

Within-Palm Localization If the haptic point locates within the palm, we employ 2D phantom sensation. To know which three haptic nodes to use for Eq. 3.1, we first find an enclosing triangle. The algorithm searches for a triangle created by three grid lines that contains the haptic point. As shown in Figure 3.6d, a single haptic point may have multiple enclosing triangles. Here, we proceed with the first triangle found since the perceived sensation would be the same regardless of the selected triangle with the independent modulation of tactors [50, 61].

Outside-Palm Localization When a haptic point lies outside the palm (Figure 3.6e), it is projected to the closer intersection between the hand boundary and the ray used for raycasting algorithm or its opposite ray (Figure 3.5c). The hand boundary is formed by as many grid lines as possible, allowing the 1D phantom sensation to create a continuous feeling. If the projected points do not lie on grid lines, they are projected to imaginary lines which actuates the closer haptic node creating the imaginary line (Figure 3.5d). Moreover, we changed the driving intensity by one-tenth of the original for the outside-palm rendering approach to differentiate from the vibrotactile feedback within actual hand [17].

By iterating through the above-mentioned geometric relationship conditions, our system enables posture-adaptive haptic rendering. If the condition is met, the described method renders the haptic point. The algorithm instead checks the condition for the next geometric relationship if the condition is not met. Here, the proposed algorithm allows adaptive haptic design where the system automatically changes the spatiotemporal vibrotactile pattern and intensities with a given haptic design. Our proposed method aims to preserve similar perceived tactile sensations for the same haptic traces in different hand postures.

Chapter 4. Haptic Experience Evaluation

We conducted two user studies to confirm the baseline performance of the integrated 1D & 2D phantom sensation and validate the posture-adaptive haptic rendering. In Study 1, we examine whether participants can identify various whole-hand vibrotactile patterns using the proposed phantom sensation approach. In Study 2, we measure the similarity of the same haptic design on different hand postures using the proposed haptic rendering method.

4.1 Study Design

We recruited 10 participants (5 females, 5 males) with a mean age of 23.0. Participants' hand sizes ranged from 15∼20 cm and all were right-handed. We carried out both studies together which took about two hours. The initial 10 minutes were used for instruction and setting up devices for participants. We provided a 10-minute break between the two studies. We provided an extra break if participants requested which happened rarely.

Figure 4.1: The setup overview of studies for (a) 1D & 2D phantom sensation recognition for whole-hand and (b) similarity for posture-adaptive haptic rendering evaluations.

Apparatus We prepared two sizes of haptic gloves (M/L & L/XL) since glove-wearing condition affects the performance of vibration transmission on the hand. We chose spandex-based sports gloves that tightly fit the hand to maintain the shape of the hand for robust hand tracking using VR HMD. Also, participants wore headphones playing white noise during the experiment to ensure participants not obtaining any hints from auditory cues like motor sounds. In Study 1, we provided a multiple-choice style desktop GUI with a keypad input to choose the stimulated vibrotactile pattern (Figure 4.1a). For Study 2, we developed an immersive study environment where participants compare the similarity of given vibrotactile feedback for various hand postures in VR (Figure 4.1b).

4.2 Study 1: Integrated 1D & 2D Phantom Sensation Recognition for Whole Hand

This study validated the baseline performance of 1D & 2D phantom sensation-based whole-hand vibrotactile sensation. We measured the information transmission rate and accuracy for identifying different vibrotactile patterns given to the whole hand. Our work focused on testing practical vibrotactile patterns that could be employed in VR applications since researchers have confirmed the perceptual localization performance of whole-hand phantom sensation [19]. Our results confirmed the feasibility of employing 1D & 2D phantom sensations to represent complex vibrotactile patterns on whole hand beyond a simple point or line-based sensations.

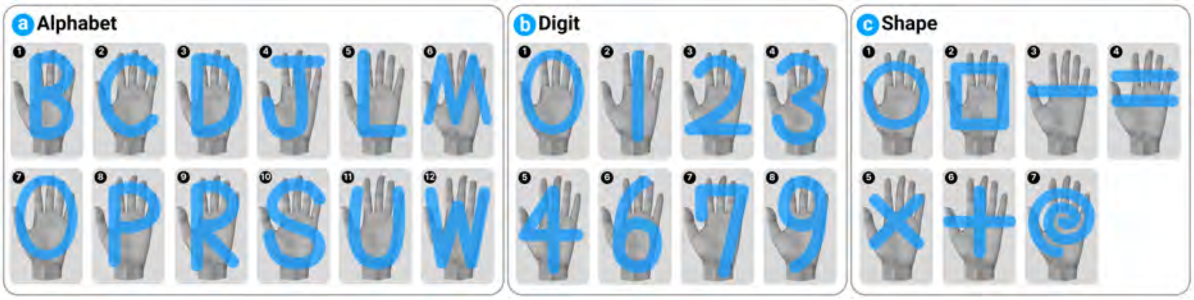

Figure 4.2: (a) Alphabet, (b) digit, and (c) shape vibrotactile pattern categories used in Study 1 of haptic experience evaluation.

We carefully chose a set of vibrotactile patterns from three categories including alphabet, digit, and shape similar to [83]. We include 12 alphabets and 8 digits to examine basic information transmission [84]. In terms of shape, we selected lines, circles, rectangles, and curved lines that could cover various regions around the whole hand. To fix the tested patterns, we carried out a pilot test with five participants to exclude easily confused patterns. We excluded alphabets with multiple strokes (*e.g.*, 'A, E, F, H, I, K, Y') and similar strokes (*e.g.*, 'C, G', 'J, T, X', 'M, N', 'O, Q', 'S, Z', and 'U, V'). Furthermore, we excluded digits like '5 & 8' which could confuse users due to different ways of writing. We came up with a total of 27 vibrotactile patterns including 12 alphabets, 8 digits, and 7 shapes (Figure 4.2) where actuation duration could take up to 1.5 seconds.

Procedure We applied vibrotactile patterns to a non-dominant hand similar to the exploratory study. To focus on measuring the performance regarding the vibrotactile sensation, we asked users to maintain a *Rest* posture. After stimulus actuation, participants chose the sensed patterns among vibrotactile patterns from the same category. For example, the participants selected 1 of 12 alphabets using a keypad when testing under the alphabet category as shown in Figure 4.1a. We offered a training session where participants experienced all tested vibrotactile patterns once. A total of 1350 responses were collected (27 patterns $\times$ 5 trials $\times$ 10 participants).

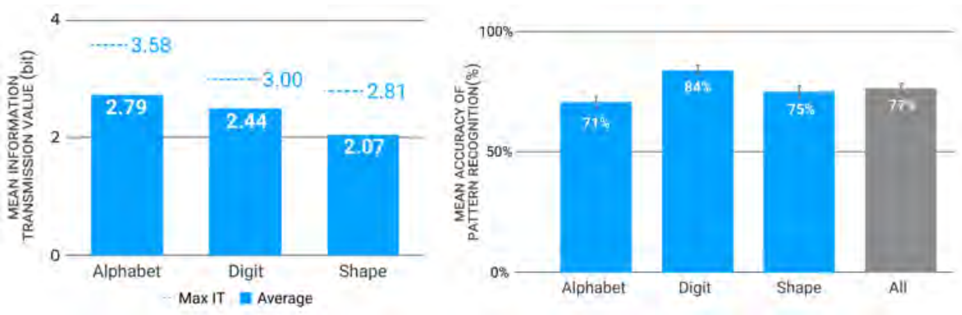

Figure 4.3: (Left) Average IT values for vibrotactile pattern categories (blue bars) with maximum IT achievable (dotted lines) (Right) Pattern recognition accuracy for individual (blue bars) and all categories (gray bar). Error bars show standard errors.

Results Out of 10 participants, we excluded one outlier that showed high response inconsistency using a 90% confidence interval. As shown in Figure 4.3, the IT for alphabet, digit, and shape categories came out to be 2.79, 2.44, and 2.07 bits accordingly and the overall accuracy was 77% (alphabet: 71%, digit: 84%, shape: 75%). Compared to whole-hand phantom sensation localization results [19], our accuracy (77%) came out better than 11 location density localization (70%). Furthermore, the overall IT (2.43) was at least higher than IT (2.09) of 2D stationary sensation [56]. Although we employed more tactors, the results still verified that participants could distinguish complicated vibrotactile patterns with proposed 1D & 2D integrated phantom sensation.

4.3 Study 2: Similarity for Posture-adaptive Haptic Rendering

In this study, we examine similarity which represents how similar the rendered haptic sensation is compared to the ground truth vibrotactile pattern shown as visual traces. We defined similarity as preserving sensed direction and distinguishing within/outside-palm sensation for given vibrotactile feedback. We tested similarity on the five hand postures (*Rest*, *Finger Gun*, *Thumbs Up*, *Fist*, and *Pointing*) to assess the performance of our posture-adaptive haptic rendering approach. We applied a set of vibrotactile patterns along with visual traces in VR for various hand postures as shown in Figure 4.1. With this study, we validate whether our proposed algorithm improves maintaining the similarity of vibrotactile feedback across various hand postures. For Study 2, we chose vibrotactile

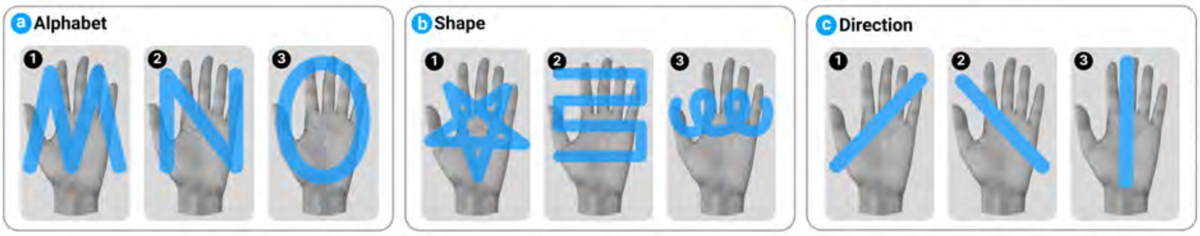

Figure 4.4: (a) Alphabet, (b) shape, and (c) direction vibrotactile pattern categories used in Study 2 of haptic experience evaluation.

patterns that can cover the entire phantom grid while effectively testing the similarity elements, including the direction and localization (*e.g.*, within or outside-palm) of stimulus. In addition, we added patterns commonly used in VR and AR game applications. Figure 4.4 illustrates the overall vibrotactile patterns including alphabet ('M', 'N', 'O'), shape (star, serpentine line, and helix), and direction (moving towards northeast, northwest, and north). We excluded short straight lines commonly used in previous studies since we aimed to test realistic haptic effects covering whole-hand sensation.

To explore the validity and efficacy of the proposed algorithm in more detail, we carried out the test under four different conditions as follows:

- **Baseline**: No posture-adaptive haptic rendering was applied.
- **Grid only**: The phantom grid was applied to adjust the direction of vibrotactile feedback for hand postures.
- **Intensity only**: Different vibrotactile intensity was applied within (normal intensity) or outside (a tenth of the normal intensity) the palm boundary.

- **Grid & intensity**: Both phantom grid and driving intensity modulation was applied.

Procedure In Study 2, participants were equipped with the HMD device (Oculus Quest Pro) and proof-of-concept haptic gloves (Figure 4.1b). Before the study, we measured participants' hand sizes and provided either M/L ($\leq$ 15 cm hand length) or L/XL ($>$ 15 cm hand length) size gloves accordingly. This guarantees to transmit equivalent vibrotactile sensation to participants with different hand sizes. The participants were instructed to rate the similarity between the sensed stimulus and visualized traces in VR on a scale of 1 to 7 (Figure 4.1b) similar to [61]. We asked participants *"How similar was the posture-adaptive tactile experience to the rendered pattern shown in VR?"*. All patterns and postures were tested in a random order. A total of 3600 responses were collected (9 patterns $\times$ 5 postures $\times$ 4 conditions $\times$ 2 trials $\times$ 10 participants).

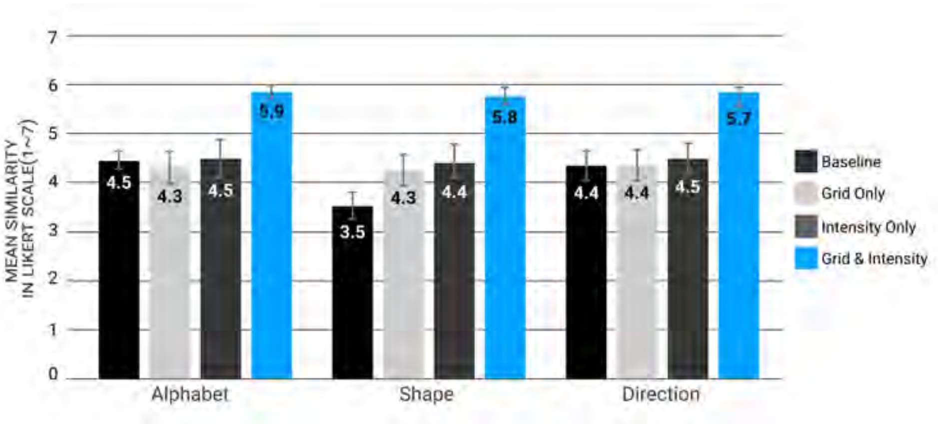

Figure 4.5: Similarity Likert Scale (1 to 7) scores for the 3 categories. The 4 bars for each category represent scores for different conditions: baseline, grid only, intensity only, grid & intensity (left to right). As shown in the graph, the full algorithm (grid & intensity) scored the highest in all categories. Error bars indicate standard errors.

Results Figure 4.5 shows that the "grid & intensity" condition had the highest similarity score 5.9 (SD=0.5) with a large margin compared to baseline score 4.3 (SD=1.1), grid only score 4.5 (SD=1.0), and intensity only score 4.5 (SD=1.1). We observed that applying either a phantom grid or localized intensity modulation did not enhance the similarity score significantly. This implies that phantom grid and localized intensity modulation should be employed together in order to improve the similarity, rather than utilizing each element separately. Among various vibrotactile pattern categories, there was a significant increase in similarity score (from 3.5 to 5.8) for the 'shape' category which consisted of frequent changes in stimulus directions. This indicates that the proposed algorithm is effective in dealing with changes in motor location for different hand postures. Overall, the results confirmed that participants found our posture-adaptive haptic rendering algorithm sufficiently capable of preserving vibrotactile sensation across various hand postures.

Chapter 5. Authoring System Usability Evaluation

In this evaluation, participants were asked to carry out a common haptic experience design task with and without the full functionality of our system. Then, we compared user experience and preference between these two conditions. Through this evaluation, we understand how users utilize the proposed solution to create meaningful haptic experiences with various hand postures. We referred to and modified the study design from previous works [27, 32, 61].

5.1 Study Design

We recruited 20 participants (10 females, 10 males) for the study with a mean age of 25.9 who were all right-handed. For this evaluation, we focused on recruiting researchers/designers experienced in either haptics or human-computer interaction-related fields (17 participants) to ensure getting feedback from those who frequently use authoring tools. Similar to the previous study, we support two glove sizes (M/L & L/XL). The overall evaluation took up to 90 minutes and we offered training sessions as well as breaks between each task.

Task Scenes We designed scenes for user study tasks under two themes: *Action* and *Puzzle*. We focused on making these scenes appear like actual gaming scenes so that haptic designers could evaluate the system in real-world scenarios. Figure 5.1 shows example scenes implemented for the two themes. For the *Action* theme (Figure 5.1a), participants designed whole-hand vibrotactile feedback for attack

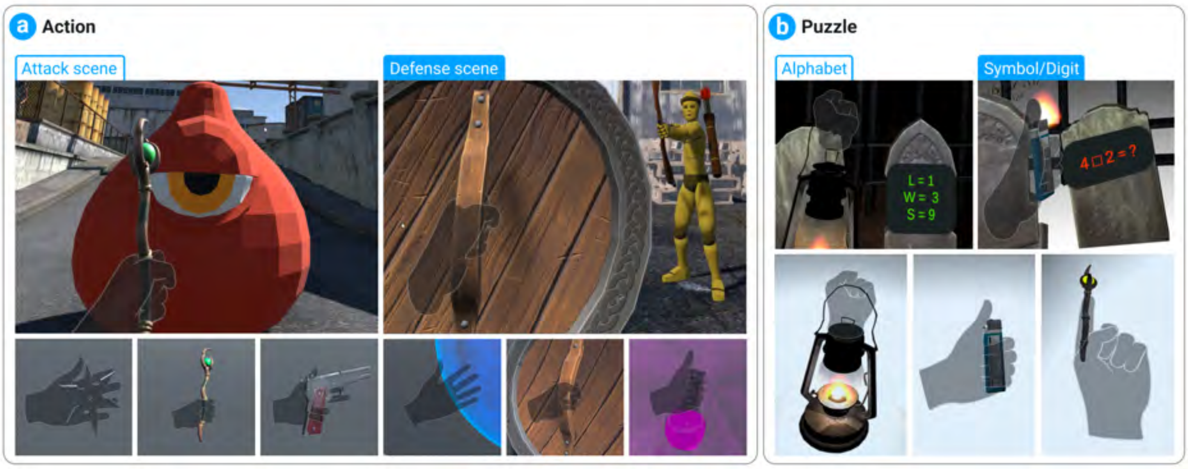

Figure 5.1: *Action* and *Puzzle* scenes along with tools participants used during evaluation. (a) In *Action* scenes, participants attack or block enemies using different tools, feeling their designs while doing so. (b) In *Puzzle* scenes, participants had to decode a puzzle through their designs using the tools as a light source.

and defense-related VFXs. These scenes had high design freedom where no specific shapes were enforced while designing the vibrotactile pattern. For Attack scenes, we used active VFXs stemming from the participant's virtual hand whereas defense VFXs were passive, coming from the enemies. Participants considered *Rest/Fist/Finger Gun* and *Rest/Fist/Thumbs Up* postures for attack and defense effects accordingly. We carried out attack and defense scenes in 2 separate sessions.

For the *Puzzle* theme (Figure 5.1b), participants designed whole-hand vibrotactile feedback to render complicated information like alphabets, mathematical symbols, and digits. We carried out 2 separate design sessions where participants had to create haptic design for either 5 alphabets ('L', 'W', 'P', 'S', and 'O') or 5 symbols/digits ('×', '+', '2', '3', and '6'). These patterns had to be designed accurately on *Fist/Thumbs Up/Pointing* postures in order to solve the puzzles. We carried out alphabet and symbol/digit scenes in 2 separate sessions.

Procedure To explore the usability and confirm the haptic sensation quality using our proposed system, we evaluated the system usability scale (SUS) and conducted a customized survey. In this study, we created a baseline called pseudo-System that represents a conventional haptic design toolkit [44, 50], which does not contain any hand posture-related features such as hand posture visualization and posture-adaptive haptic rendering. By comparing the two conditions, we expect to understand the effect of adopting hand posture-related features in the haptic design process.

Prior to the study, participants went through a training session followed by instructions on the overall experiment procedure. From the pilot study, we noticed that users require some training sessions to get used to basic VR interactions such as the pinching motion. We expected that the training session would help prevent the existence of prior VR experience from affecting the SUS score. Participants practiced hand postures and conducted the Oculus built-in tutorials [27] to get used to the VR environment for up to 5 minutes.

We split 20 participants into 2 groups to counterbalance the order of test conditions. Each group carried out 4 design sessions in total as follows:

- Group1: pseudo-System (*Action* & *Puzzle*)→System (*Action* & *Puzzle*)
- Group2: System (*Action* & *Puzzle*)→pseudo-System (*Action* & *Puzzle*)

Within the same type of design scene (*Action* or *Puzzle*), we randomized and counterbalanced the order of tasks (*e.g.*, *Action*: attack and defense effect & *Puzzle*: alphabet and symbol/digit). Before starting each design scene, as a demo, we let each participant experience the scene they would design using haptic patterns designed by previous participants.

After each design scene, participants answered the SUS questionnaire and provided qualitative feedback on their design through survey questions. After completing all design sessions, we interviewed the participants to collect their experiences. To remove potential bias from adaptation and order effect, we only used responses from the last two sessions for SUS analysis.

Users also completed a Likert-type (scaled 1∼7) survey regarding the quality of haptic sensation and user interaction using the proposed system after each session (Figure 5.3). We got responses only for the system condition since we were interested in user experience with the full functionality of our system. We modified existing questionnaires for authoring tools [85, 27] in order to understand participants' experiences of haptic design. We also asked participants' opinions on a haptic design created by others after the demo for each design scene. They evaluated if *"The designed haptic patterns matched their corresponding hand gestures well"* (Q2 in Figure 5.3). This enables us to compare how participants comprehend haptic design by others, not just their own.

5.2 Results

The overall SUS score was 71.0 (SD=17.3) for the pseudo-System condition (Figure 5.2a) and 81.0 (SD=14.2) for the System condition (Figure 5.2b). The SUS scores for both conditions were greater than 70, indicating satisfactory usability for the in-situ VR design process with sketching. The System condition resulted in a rise in the SUS score by 10 compared to the pseudo-System. Figure 5.2 shows the overall distribution of SUS scores for both conditions. More than half of the participants gave a score greater than 80 for the System condition. This clearly indicates that the system usability improved with the proposed posture-related features from the proposed framework.

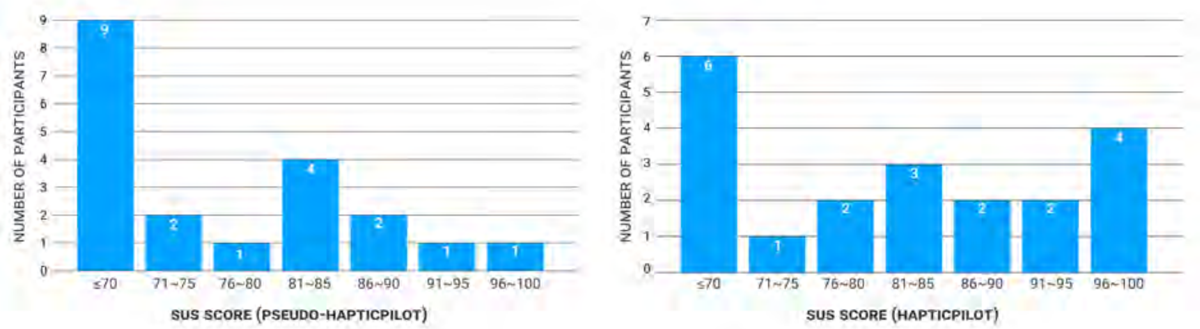

Figure 5.2: Distribution of SUS score in pseudo-System and System conditions.

The overall System-related Likert-type question ratings are shown in Figure 5.3a. In general, users agreed with the positive effect of employing hand posture-adaptive features for the haptic design process. Users responded that they could design as intended using the system (Q1: AVG=5.5, SD=2.0). Participants were satisfied with the haptic design created with the System for different hand postures (Q2-2: AVG=5.3, SD=2.0). Here, we noticed that participants generally favored their own design (Q2-1: AVG=4.3, SD=1.6 vs. Q2-2: AVG=5.3, SD=2.0) due to individual differences in drawing/writing shapes/digits. *"I was confused with others' haptic design since the order of strokes and starting location was different from how I would draw/write it. (P15)"*. Moreover, participants responded that having the virtual hand alter the posture throughout the design stage helped them to create accurate designs (Q3: AVG=5.8, SD=1.0). *"It is comfortable to design with hand posture support which makes my design task simpler. (P2)"*. In terms of in-situ design with visualized traces, users reported that it was straightforward to utilize the traces (Q4: AVG=6.0, SD=1.0) and that the in-situ VR design process was intuitive (Q5: AVG=6.2, SD=1.2). *"It is very useful to design while seeing VFX. The VFX helped me confirm that my design worked as intended. (P8)"*.

We also compared the Likert rating between *Action* & *Puzzle* task scenes. *Action* scene supports more design freedom since users have to create the vibrotactile pattern from a scratch without any shape reference. On the other hand, *Puzzle* scene requires participants to design familiar patterns like alphabets, digits, and symbols. Figure 5.3b shows that the proposed hand posture-adaptive features worked better with the task involving more design freedom (*Action* scene). When experiencing other people's designs (Q2-1), users were more satisfied with creative patterns (*Action* scene: AVG=5.2, SD=1.0) over fixed shape patterns (*Puzzle* scene: AVG=3.4, SD=1.0). This aligned with our previous finding that each individual prefers their own writing/drawing style for vibrotactile patterns. We also noticed that users found System more intuitive in the *Action* scenes where the design objectives were more abstract. This tendency was statistically observed ($p < 0.03$) from Q5 (*Action*: AVG=6.4, SD=1.0 vs. *Puzzle*: AVG=6.0,

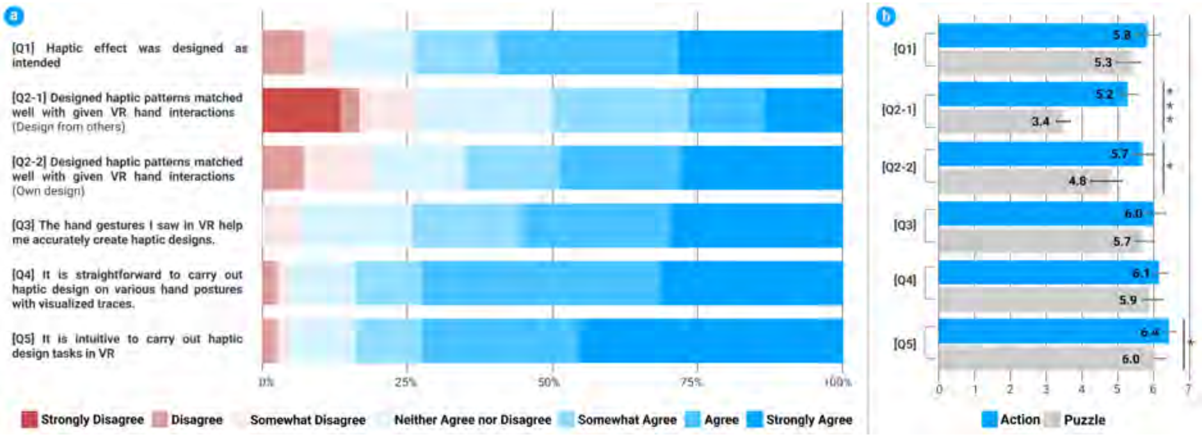

Figure 5.3: (a) The occurrence of response to questionnaires. (b) Responses to *Action* (blue) and *Puzzle* (gray) scenes.

SD=1.0). Figure 5.4 illustrates vibrotactile patterns designed using our System. It is interesting to note the variety of vibrotactile pattern design strategies using the full System. For example, some participants focused on drawing haptic traces within the hand region for different postures (*e.g.*, *Finger Gun* posture with 'Attack' in *Action* scene) to concentrate vibrotactile sensation whereas other participants utilized the whole drawable area to deliver shape information (*e.g.*, *Thumbs Up* posture with digit '6' in *Puzzle* scene). When using the pseudo-System condition without hand posture-related features, participants reported difficulties in designing vibrotactile patterns to accommodate different postures. Without the posture-adaptive features, designs made on a fixed hand posture had limitations in delivering appropriate sensation. *"I felt different sensations depending on the hand movements. (P7)"*. As a consequence,

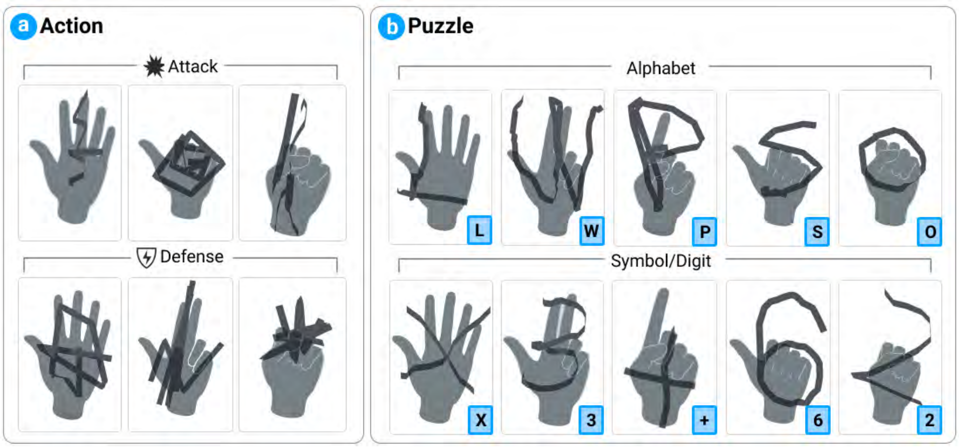

Figure 5.4: Haptic design from participants using our system for (a) *Action* and (b) *Puzzle* scenes. Various design strategies and preferences were observed where some preferred utilizing within-palm regions and others used wider spaces to focus on rendering the whole shape.

participants either had to make modifications repeatedly from their original intended design or had to devise their own methods. *"When the vibration is applied to fingers, I have to modify it constantly. So I would rather draw it on the palm. (P2)"*. With the System condition, on the other hand, participants were able to design consistent patterns in various postures. *"I could recognize original patterns on different hand postures. (P20)"*. From a design perspective, the proposed framework simplified the complex design process to accommodate different hand postures. *"It was convenient to design on different virtual hand postures directly since I did not have to think about changes of vibrotactile sensation due to posture changes. (P2)"*. This also relates to the satisfaction of the output design. *"I edited less because I was satisfied with the automatically generated patterns. (P2)"*.

Chapter 6. Applications

Our study results showed that our framework is capable of preserving directional sensation and helping users distinguish between within- and outside-palm haptic points. Using these insights, in this section, we highlight specific use case scenarios using glove-type haptic devices where our framework could be exceptionally helpful.

Figure 6.1: The user designs (a) VR VFX for weapons with different hand postures while receiving the same haptic experience, (b) uniform haptic notification for incoming mail regardless of the user's hand postures, and (c) haptic guidance with consistent direction sensation for tools with different hand grasps.

VR Immersion Improvement Nowadays, users utilize controllers to carry out haptic design tasks for VR VFX where users' hand postures are often restricted. Although various haptic gloves have been introduced, it is difficult to design haptic experiences for these devices because of unpredictable hand postures. Our authoring framework creates versatility for haptic designs so that the same haptic experience can be maintained over various hand postures, ultimately improving VR immersion with haptic gloves in game scenes as shown in Figure 6.1a.

Effective Notifications Our framework could provide design support to bring more effective haptic notifications or interruptions for VR. For common notifications like calls or texts, haptic design should provide a balanced sensation to provide effective interruption while minimizing irritation from users. Utilizing an in-situ authoring framework, users could easily iterate the design drafts to provide balanced sensations over various hand postures. Moreover, it provides adequate design tools for users to create distinctive haptic designs for different notifications in various contexts. Figure 6.1b illustrates how it can help design adequate notifications in a virtual office environment.

Enhanced Guidance & Training Our framework preserves the stimulus's directional sensation on various hand postures, which allows such information to be transmitted accurately. This can be mainly used for vibrotactile navigation in VR [17] such as maps or more specific training simulations. Simple navigation may not require users to change their hand postures. However, more complex training simulations used for aviation or surgery require users to use different postures depending on the task. Figure 6.1c shows an example of designs used for navigation in a training scenario.

The above-mentioned scenarios illustrate a glimpse of potential applications using our system, which are selected to highlight the results of our studies. It could also be employed for any other applications that require designing whole-hand vibrotactile sensations on various hand postures with minimal information loss.

Chapter 7. Discussion

In this section, we interpret the results and share our observations from user studies. Furthermore, we discuss the current limitations of the proposed authoring toolkit and suggestions for future iterations.

Information Transfer vs. Design Intention Our approach showed superior performance in rendering digits and alphabets compared to shapes. In Study 1, our algorithm scored higher accuracy in the digit category compared to the shape category. For Study 2, the alphabet scored the highest similarity score (5.9) among all. However, users rated the usability of *Action* scenes higher than *Puzzle* scenes which used familiar alphabet, symbol, and digit in Study 2. We assume this is due to different writing styles of alphabets and digits for people with various backgrounds. For creative patterns used in *Action* scenes, users were generally satisfied as long as the user "feels" the design intention. This also tells that users would set higher standards for vibrotactile feedback conveying preconceived shape information like alphabets and digits.

Towards Personalized Haptic Design During the usability evaluation, we observed that participants preferred their own designs (Q2-2: AVG=5.3, SD=2.0) over designs made by others (Q2-1: AVG=4.3, SD=1.6). From the result, we infer that users prefer the personalized and customized haptic design over the general vibrotactile patterns. In this regard, we believe that a user-friendly haptic design toolkit with a low-task load like our framework would benefit not only existing hapticians but also every user who likes to design his/her own vibrotactile pattern.

High Standards for Authoring Interface During the qualitative feedback, System condition received favorable scores (≥ 5.8) for interface-related areas (Q3∼Q5). We assume positive feedback came from adopting a familiar interface design (button based 3D UI) and interactions (pen-based sketching). However, participants tend to compare our interface with higher standards such as commercially available VR drawing applications. Thus, we believe the current usability score is at the high end as a research prototype considering users' high standards.

Limitations and Future Works The occlusion in overlapped hands limits vision technology used in current industrial VR headsets. This not only reduced the system usability but affected the implementation details for the algorithm. Since the current hand tracking system cannot detect the contact relations between fingers or the palm, the contact status had to be inferred from the relative positions of haptic nodes in phantom grid construction. We could overcome this issue by employing haptic gloves with embedded physical sensors. The gloves with EMG or IMU sensors could be alternative to vision-based hand tracking [86]. Moreover, combining the vibrotactile feedback and sensing into a single glove could solve poor posture recognition and finger contact detection.

In this work, the toolkit was designed to support predefined representative hand postures only on the left hand. However, the same algorithm could be mirrored to the right hand to support bimanual haptic design. A future approach would be utilizing the hand posture-capturing functions from commercial SDKs to add and modify users' hand postures freely. Furthermore, we plan to provide it as plug-ins that could be integrated into real game development studios.

Since the algorithm was based on a 2D phantom sensation method, the haptic sketches were drawn in a 2D plane on hand. Also, the supported hand postures were restricted to those where the fingers were either entirely extended or flexed to touch the palm. By integrating other methods such as out-of-the-body sensation [17, 59, 60], however, we expect to expand the rendering domain into 3D spaces.

Chapter 8. Conclusion

In this paper, we present an in-situ VR haptic authoring framework with a posture-adaptive haptic rendering algorithm. We demonstrate a novel rendering plane called phantom grid which is used to design patterns and utilize 1D and 2D phantom sensation to provide whole-hand tactile feedback for various hand postures. To evaluate haptic experience, we examined the IT and accuracy for 1D & 2D phantom sensation-based whole-hand vibrotactile sensation from 10 participants. In the authoring system usability evaluation, we collected qualitative feedback and an overall SUS score of 81.0 from 10 participants which indicates that user hand posture-related features of our system are efficient and user-friendly. Using these observations, we demonstrated application scenarios where our authoring framework enhances VR immersion. Eventually, we hope that our system and the attempts we made can encourage HCI haptic related researchers studying haptic experience and its design process.

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