Generating Haptic Textures with Vibrotactile Under-clothing Wearables

Daichi Kariyama [1], Christian Arzate Cruz [2], Miki Matsumuro [3], Fumihisa Shibata [1], and Asako Kimura [1]

[1] *Graduate School of Information Science and Engineering, Ritsumeikan University, 1-1-1 Nojihigashi, Kusatsu, 525-8577, Japan*

[2] *College of Information Science and Engineering, Ritsumeikan University, 2-150 Iwakura, Ibaraki, 567-8570, Japan*

[3] *College of Information Sciences and Technology, Penn State, University Park, PA, 16802 USA*

Abstract

In recent years, immersive technologies consisting of Virtual Reality (VR) and Mixed Reality (MR) are perceiving high interest from various fields. An open challenge in the VR community is to investigate appropriate ways to deliver notifications to users. This paper proposes to use under-clothing wearables to provide vibrotactile feedback on multiple body locations and investigate the generation of haptic textures using wearable devices. Two user studies were conducted to examine the vibrational parameters' effect on perceived experiences. The first study (N = 6) aims to investigate the minimal needed force for the different vibration textures to be perceived by users. In the second study, a human-computer interaction researcher (N = 1) mapped the texture features to physical features, such as softness and sharpness. This study is a first step towards designing multiple haptic textures for wearables that can provide the appropriate experience for a given scenario (e.g., obstacle avoidance and guidance).

Keywords

Vibration, Haptic Texture, Wearable Device

1. Introduction

In recent years, immersive technologies such as Virtual Reality (VR) and Mixed Reality (MR) have gained interest from various fields, including education, research, communication, medical supply, and entertainment. These technologies provide immersive experiences with a vast degree of freedom (DOF) compared to more conventional technologies.

However, due to the immersive technologies' high DOF and immersion, two main challenges arise respectively. Due to the immersion, users can lose track of their bodies in the real world (P1), which can trigger accidents, e.g., hitting an obstacle. Second, the high DOF can cause users to experience fear of losing out (P2). Both challenges are open problems in the VR community.

This paper proposes to use under-clothing wearables to provide vibrotactile feedback on multiple body locations. Some of the applications of our proposed devices and haptic feedback texture include guiding users to a designated content (P2) and preventing them from colliding with real-world obstacles (P1).

For P2, previous works have proposed the addition of the visual effect as an effective approach. This approach aims to guide users by

APMAR'23: The 15th Asia-Pacific Workshop on Mixed and Augmented Reality, Aug. 18-19, 2023, Taipei, Taiwan

*Corresponding author.
EMAIL: kariyama@rm2c.ise.ritsumei.ac.jp (Daichi Kariyama), arzate.christian@gmail.com (Christian Arzate Cruz), mmm8968@psu.edu (Miki Matsumuro), fshibata@is.ritsumei.ac.jp (Fumihisa Shibata), asa@rm2c.ise.ritsumei.ac.jp (Asako Kimura)

adding certain objects, such as arrows and maps, which generally provide information through the object's metaphor that is already established in the real world. The high accuracy of this approach is proven by several previous studies [1] [2].

Although the visual effect approach has high accuracy as a guidance method, the overtness of the objects used in the method, like the examples written above, became a hindrance to the acquisition of the original visual information of the content. New approaches were advocated to further improve the comprehensive performance of the guidance.

This paper proposes to use under-clothing wearables to provide vibrotactile feedback on multiple body locations. In this manner, the system could deliver notifications that do not interfere with the visual content on the head-mount displays (HMDs). Hypothetically, this method could be used to tackle P2, that is, this system could be used to guide users to designated content.

Also, previous works adopted vibration feedback as a new method to provide guidance. Nonino *et al.* [3] used two vibration-presentable controllers to navigate a user to a designated area in a virtual space, by guiding their attention toward the direction of the objective. The effectiveness was proved by comparison with the non-guided results. However, this method lacks efficiency and effectiveness compared to the visual approaches. Hypothetically, the low performance of this method is caused by a lack of granularity in the guidance information. This method can only provide the rotation direction, which is conveyed by the toggle vibration of the controller closer to the designated area.

Compared to this method, our approach with wearable devices has the advantage of the number of presentable vibrational feedbacks. The vibration motors mounted on multiple locations of the user's body could enlarge the granularity of the guidance information.

Regarding P1, there have been efforts that consist of utilizing MR technology to convey information about real-world obstacles while experiencing VR content. Wu *et al*. [4] advocate a method that adds a wireframe of the real-world obstacles on the edge of the content presented. The real-world obstacles are 3D scanned in advance of the experience. This method allows the user to visually recognize the real-world obstacle's position. Although this method enables the user to avoid collisions according to the direct and clear information it provides, the generated wireframe interferes with the original image presented. In contrast, our proposed method has the advantage of not utilizing any visual effects in presenting the guide for obstacle avoidance. This makes it possible for the user to recognize real-world obstacles without diminishing the immersion of the content.

As a first step towards designing multiple haptic textures for wearables that can provide the appropriate experience for either obstacle avoidance or guidance scenarios, an investigation was conducted to examine the haptic textures using our wearable devices. The results of this experiment are to be a basis for designing the future system of Attention Guidance and Obstacle Avoidance. Two user studies were conducted to study how different vibration parameters impact the haptic experience. In the first study (N = 6), a vibrotactile threshold investigation took place to find out the minimal needed force for the different vibrations to be perceived by users. In the second study, a human-computer interaction researcher (N = 1) was asked to map the texture features to physical features such as softness and sharpness.

In Chapter 2, there will be an introduction to the previous research pieces related to this paper. Chapter 3 will describe the configurations of the vibrotactile under-clothing wearables. Chapters 4 and 5 will each describe the result and discussion of the two experiments conducted to investigate the vibrotactile textures presented by the proposed system of this paper. In the last chapter 6, there will be a discussion about the conceivable applications, feature work, and a conclusion of the overall paper.

2. Related Work

Our paper refers to many previous studies conducted. Those studies could be categorized into wearable devices, vibrotactile stimulation, and applications such as attention guidance, and obstacle avoidance.

2.1. Wearable Device

Studies have recently advocated wearable devices as a tool to provide haptic feedback. In previous studies, one of the most common body locations considered to provide haptic feedback is the wrist. There are numerous studies conducted to advocate devices and systems that aim to present haptic feedback to the user's wrist. These devices mostly consist of multiple haptic feedback presentation parts and a fastener belt that is meant to be wrapped around the wrist [5] [6] [7].

The hands and fingers are other locations of the body wearable device research that has been ongoing rapidly. Hinchet *et al*. [8] advocated a glove-like device that presents force feedback to the hand with electrostatic brakes and piezoelectric actuators. This device prevents the user's hand from grasping, allowing the hand to stop in the shape of a virtual object.

In another previous study, Bhatia *et al*. [9] adopted a unique and simple structure for a wearable device that utilizes magnets for fastening the device onto the user's clothes. This structure consists of two magnets, each located inside and outside the clothes, anchoring themselves to the clothes. In their research, this structure was adopted to mount their haptic feedback devices on multiple locations of the participant's upper body to investigate the haptic feedback perception.

Also, Al-Sada et al.'s research [10] presented a robot arm mounted on a waist belt to provide haptic feedback. This robot arm can present multiple types of haptic feedback, including general feedback like shear and harsh force, and gestural feedback like poke. This device is also capable of providing these types of feedback in a vast space of the body.

2.2. Vibrotactile Stimulation

In the research of Yun *et al.* [11], they aimed to examine the phantom sensation generated by multiple vibrations. The vibration will be presented in order with half of its rendering time overlapping with the next vibration. This made the user perceive a high-quality phantom sensation, measured by the perceived continuity of illusory movement and the consistency of perceived intensity. This system consists of four different functions and three values of the vibration presentation times to simultaneously displace the vibration's intensity. Multiple vibrations generated by these parameters were presented to the participants to examine the effectiveness of the phantom sensation occurrence.

Strohmeier *et al.* [12] researched to investigate the impression of the perceived texture of multiple vibrations generated by three parameters. The slider device used in this experiment generates vibrational feedback while the user is moving the moveable part of the device. The parameters of the presented vibrations are granularity (pulses per cm), amplitude, and timbre. They investigated how each parameter affects the participants' impression by making them evaluate multiple vibrations with several experiment measures, adhesiveness, roughness, bumpiness, and sharpness.

Nakagawa *et al.* [13] developed a shoe-shaped device to present vibrational feedback to the user's feet. This device consists of two vibration motors each located on the toe and the heel of the shoe. The system can present several vibrations, e.g., walking on snow, rainy road, and stone crushing. Though not all of these vibrations' waveforms were not shown in the paper each vibration type seems to consist of an original waveform resulting to generate a unique texture.

Jacob *et al.* [14] developed a system that provides navigational assistance conveyed by vibrational feedback. The system's feedback is configured with a unique presentation time of vibration, and each type represents a different instruction e.g., path following, signaling a change of direction in the path, and alerting the user that they have reached an area that includes a tactile pavement near a pedestrian crossing.

In research conducted by Liao *et al*. [15], a system consists of six vibration motors mounted on a belt worn on the calf. This system aims to produce a phantom tactile sensation between the vibration motors. By generating a phantom tactile sensation, this system can present more direction information than the number of vibration motors in the system.

Xiong *et al*. [16] developed a waist-belt device consisting of three motors for each front, right, and left direction. There are two methods of vibration activation investigated in this research. In dynamic vibration, vibration motors were activated in a certain order to present a walking direction e.g., three motors activated in order from the left, center, to right meaning walk straight forward. Static vibration, which showed a higher effectivity than dynamic vibration, presents a walking direction by activating the three vibration motors that represent the designated direction at the same time.

2.3. Applications

2.3.1. Attention Guidance (AG)

Some studies that adopt the vibrational approach for attention guidance, point out the relationship with the studies conducted about walking guidance for limited vision people [4].

Xiong *et al*. [15] have explored the guiding methods that do not require visual acceptability, and one of those methods aims to guide by the stimuli provided by multiple vibration motors. Although this research successfully reduced the cognitive load of the participants in a certain situation, the guidance provided by the belt device they developed has a limit to its guiding direction. The device can only provide 2DOF guidance due to the layout of the vibration motors.

Many past studies have considered the objects used in the visual effect AG method. Wallgren *et al*. [1] have conducted a user study with three types of methods that each utilize different visual guide objects: arrow, butterfly guide, and radar. Their results show that participants achieved higher scores with a target-finding performance while being supported by the visual effect AG than a trial with no guidance, regardless of the object type.

Another research conducted by Speicher *et al*. [2] investigates AG methods suitable for video content with 3 DOF. They created a short video of up to 60 seconds, for each of their AG methods to compare how accurately the participants could identify the blinking object that changes in each video. The accuracy of this study is measured from the accuracy rate of the indication of the object and the type of AG method presented. The result shows that the trial with an AG scored significantly higher than the trial without it.

Compared to these studies, Nonino *et al*. [3] conducted a study that emphasizes the subtleness of the AG. This study advocates a temporal luminance modulation and a haptic feedback AG method. The temporal luminance modulation AG method uses a circle-shaped object that appears temporarily when an AG is needed. The researchers compared the effectiveness of this AG method with a 3D arrow AG method similar to Jan Wallgrun *et al*.'s research [1], though the design was more subtle. A search task experiment was conducted in a virtual 4 × 7.5m room to compare the effectiveness of the methods. The 3D arrow AG method was most effective in terms of search time, and the more subtle temporal luminance modulation AG method came close to its result.

The haptic feedback method advocated by Nonino *et al*. [3] is designed for the user to hold a vibration-presentable controller in both hands. A single controller vibrates at a time to convey information about the preferred rotation direction to the user. The search time results are shown in Figure 1. The haptic feedback method scored higher than the no AG trials but was not efficient as the 3D arrow AG method.

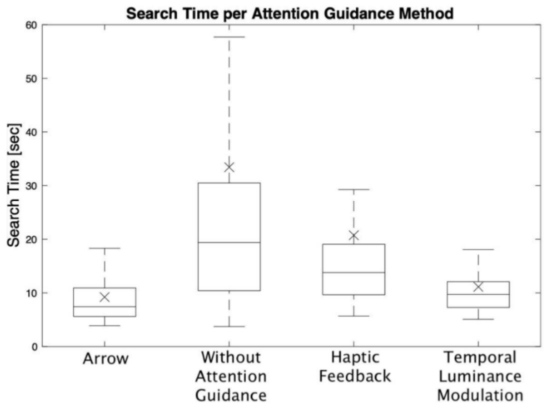


Figure 1: Box-and-whisker plot of the search time per AG method [3]

Also, some studies advocate a vibration-presentable belt device for different body parts. Paolocci *et al*. [17] developed a belt device for the waist. This device mounts four vibration motors to navigate and convey the direction of the task to the user. Schaack *et al*. [18] developed a belt device for the neck. As there are three layout patterns in this device, this study aims to develop a navigation system that guides with vibrational feedback around the neck.

Though these research pieces pursue providing an efficient AG, they cannot provide AG in a 3DOF situation due to their vibration motor layout.

In the study conducted by Pescara *et al*. [7], they developed a device consisting of 10 vibration motors, mounted on a wristband. This study aims to provide attention guidance for control room staff constantly scanning multiple monitors for alerts. They have proven their device's effectiveness in task completion time diminishing, by activating the vibrator in the direction of the designated monitor.

2.3.2. Obstacle Avoidance (OA)

In many studies that aimed to provide a guide for collision avoidance with a real-world obstacle in VR content, visual approaches were adopted e.g., Kanamori *et al.* [19], Kim *et al.* [20], Wu *et al.* [4]. Although these research pieces adopt unique methods in molding the obstacle's visual information, they commonly scan the obstacle in a certain way and synthesize it into image-based VR content. Jaeeun Kim *et al.*'s research advocates a method that aims to reduce the negative effect of the visual information of the

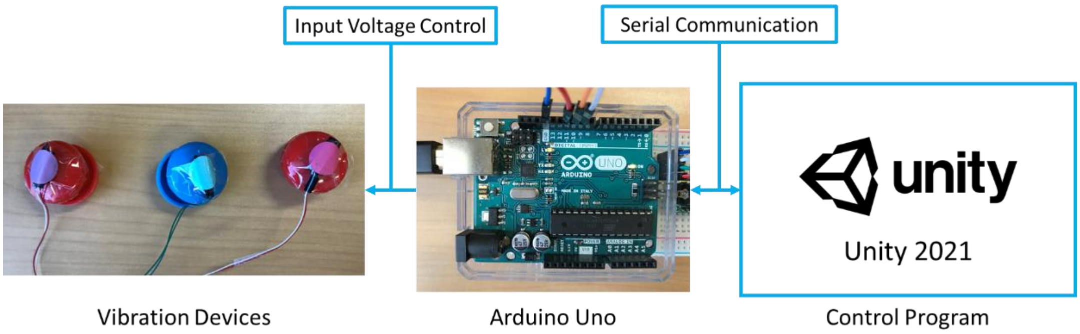


Figure 2: System division

obstacle added to the original content. Though this study concludes that their method failed to decrease the overtness of the added information, these studies show the uprising need for a subtle OA method.

Nakagawa *et al.* [13] have developed a shoe-shaped device that detects obstacles with a distance sensor mounted on the toe of the device and presents vibrotactile feedback from the heel. Though this system can assist the user's collision avoidance through subtle feedback, the presentable position is limited to the foot.

2.4. Research Overview

A vibrotactile under clothing wearable to examine the textures of multiple vibration presentations on multiple body locations with the structure obtained from Bhatia *et al.*'s research [9]. Then the vibrations to present with this device were designed, regarding the parameters, rendering method, and duration time of the vibration. These parameters refer to Yun *et al.*'s research [11]. After all the preparation was completed, two experiments were conducted. The first was to verify the minimum vibrational intensity the user needs to recognize the feedback, and the second was to examine the vibrational features perceived by the user.

3. Vibrotactile Under-clothing Wearables

This experiment aims to examine the vibrational stimuli threshold in multiple locations of the body. To carry out our examination, a prototype of the 3DOF AG system was developed, which can provide vibration in three separate locations. As shown in Figure 2, this system is divided into three divisions. The vibration devices,

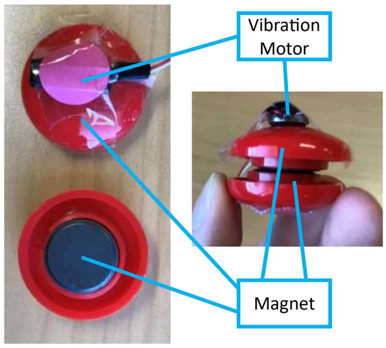


Figure 3: Vibration device

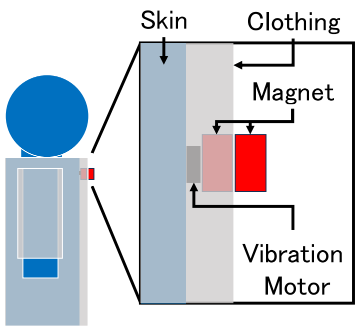


Figure 4: Structure advocated in Bhatia et al.'s research [9]

microcomputer Arduino Uno, and a control program.

3.1. The Vibration Device

The vibration device developed is shown in Figure 3, which consists of a vibration motor, and two magnets. There are three of these devices in this system, and in the experiment, each of them presents vibrational stimuli to a separate location of the body. This device adopts the structure of Bhatia *et al.*'s research [9] which utilizes magnets as a fastener to anchor the haptic feedback device to the user's clothes. As shown in Figure 4, in this structure, the haptic feedback device with a magnet will be placed inside the user's clothes and fastened by another magnet positioned outside.

Table 1
Specification of the vibration motor

Voltage range	2.5 to 3.5V
Size	10mmϕ x 2.0mm
Weight	2 g

The specification of the vibration motor used in this device is shown in Table 1.

3.2. Parameters of the Haptic Texture

There are two parameters, rendering method and duration time, configuring the vibrations. These parameters were taken from the research conducted by Yun *et al*. [11]. Though their study aimed to investigate the phantom tactile sensation generated by multiple vibrations, these parameters were appropriate to generate unique vibrations for this paper.

3.2.1. Rendering Method

There are four types of rendering methods defined in this paper: Linear, Log, Gaussian, and Square. These rendering methods are a parameter set to designate a single vibration's input voltage displacement. The graph of the displacement caused by each type of rendering method is shown in Figure 5 and the equations of each rendering method are shown in Table 2. Descriptions of the terms written in Figure 5 are as follows: (1) Output Voltage meaning the output voltage of the microcomputer (2) $Output_{max}$ meaning the designated maximum output voltage for a single vibration (3) T meaning the duration time for the output to reach the maximum value, which equals to the second parameter.

3.2.2. Duration Time

The duration time parameter consists of three values, 0.05ms, 0.1ms, and 0.15ms. This parameter is set to designate a duration time for the output voltage to reach the maximum value, which is shown as the T value in Figure 5. The value, 0.15ms refers to the shortest duration time Yun *et al.* [11] defined in the study which requires the participants to feel the vibration. In our experiment, the goal was to examine the stimulus threshold of the vibrotactile stimuli. Therefore, the other two values are 0.05ms and 0.1ms shorter that the former value, which could be hypothesized to cause a decrease in perceptibility.

3.3. Implementation

3.3.1. Control Program

The control program is constructed with Unity (Version: 2021.3.11f1). This program transmits the key input data obtained on the Unity program to Arduino Uno in a format capable of transmitting with serial communication. This program allows the experiment conductor to control the presenting vibration with simple keyboard inputs. The specification of the PC used to build this program is shown in Table 3.

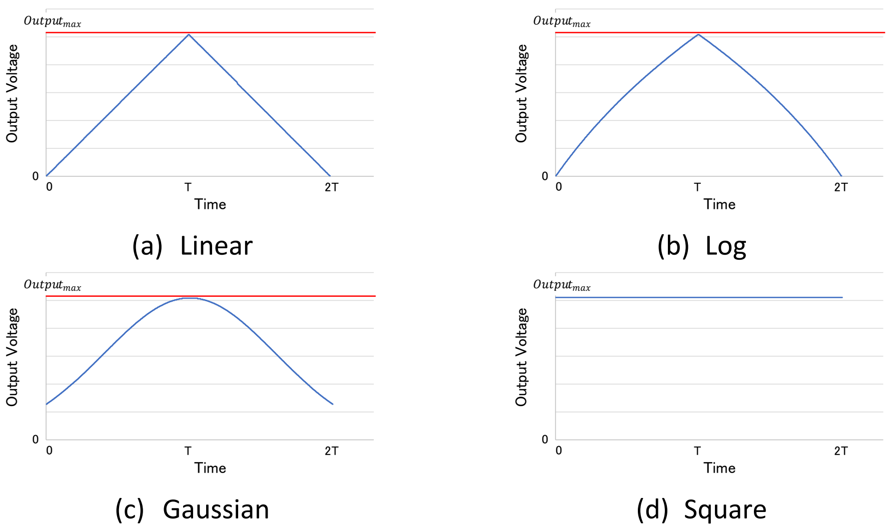


Figure 5: Graphs of displacement caused by each rendering methods

Table 2
Equations of each rendering method

Linear	$Output = \begin{cases} Output_{max}\left(1 - \frac{\lvert t-T \rvert}{T}\right) & if\ \lvert t-T \rvert < T \\ 0 & otherwise \end{cases}$
Log	$Output = \begin{cases} Output_{max}\log_2\left(2 - \frac{\lvert t-T \rvert}{T}\right) & if\ \lvert t-T \rvert < T \\ 0 & otherwise \end{cases}$
Gaussian	$Output = Output_{max}\exp\left\{-\frac{1}{2\sigma^2}\left(\frac{t-T}{T}\right)^2\right\}$
Square	$Output = Output_{max}$

Table 3
PC specification

CPU	Intel Core i5-10400
Memory	16.0 GB
GPU	NVIDIA GeForce RTX3060
OS	Windows 10 Pro Education

Table 4
Specification of Arduino Uno

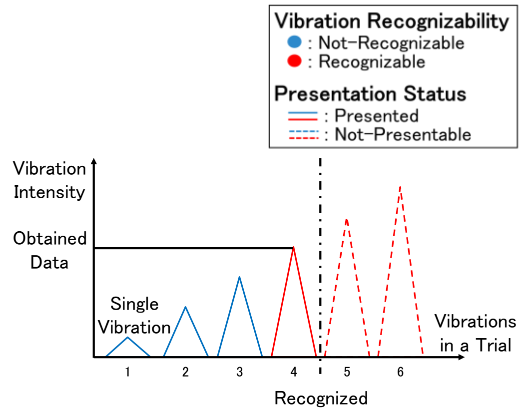
I/O Voltage	5V
Digital I/O Pins	14
Analog input pins	6
Flash memory	32KB
Clock speed	16 MHz

3.3.2. Microcomputer

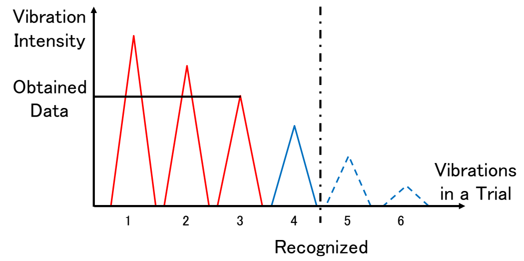
The microcomputer, Arduino Uno controls the vibration motor according to the data obtained from the serial communication with the PC with the control program. Arduino Uno possesses a function that enables it to change its output voltages within the range of 0V to 5V in 256 steps. By using this function, Arduino Uno can control the vibrational stimuli according to the values of the parameters designated. The parameters and their values will be described in 4.3.2 Vibrational Parameters. The specification of the Arduino Uno is shown in Table 4.

4. Stimulus Threshold Experiment

In this chapter, using the developed system described in Chapter 3, an experiment was conducted, which aimed to examine the threshold of vibrational stimuli presented to multiple locations of the body. Regarding the fact that this is a preliminary experiment for developing a superior system, appropriate values of the vibrational parameters, and the body locations to present the vibrations were selected.



(a) A diagram of a single trial (ascending)



(b) A diagram of a single trial (descending)

Figure 6: Diagrams of a single trial in the experiment

4.1. Overview

In this experiment, the participants will be presented with a series of vibrations with ascending or descending maximum intensity. A series of vibrations is presented in a single trial and the graphs in Figure 6 are the descriptive sketches of an ascending and descending trial. Each of the triangles in Figure 6 represents a

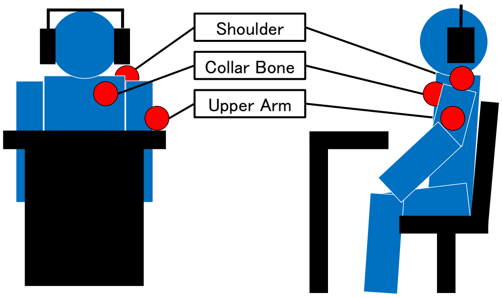


Figure 7: The posture of the participants during the experiment

single vibration. In both types of trials, ascending and descending, participants will be instructed to notify the experiment conductor when they notice a shift in the recognition state, meaning that they started or stopped recognizing the presented vibration. Participants will repeat the trials two times each for all the vibration type and body location combinations. There are 12 vibration types (combinations of four rendering methods and three duration times), three body locations, two trial types (ascending and descending), and two trials for each combination, totaling 144 trials for this experiment.

The three body locations are the shoulder, collarbone, and upper arm. These locations are obtained from Bhatia *et al.* 's [9] study, which examines the perceived features of several haptic feedbacks in six upper body locations. Three locations shown in Figure 7 were adopted, due to the lowest error rate of the perceived location identification experiment in the previous study.

The vibration intensity is controlled by the 256-stepped output voltage of a microcomputer. A single step represents about 0.02V of change in the output voltage, due to the maximum output voltage being 5V. As shown in Figure 6, the maximum intensity of the single vibrations in a trial differs from one another. The maximum intensity of the single vibrations varies between 45 and 255 steps of the output voltage, and the contiguous single vibrations' maximum intensity displacement is equivalent to 5 steps, meaning about 0.1V. The output voltage of the minimum step 45, generated vibration with a minimum intensity perceivable with the finger, which has a higher vibrational perceptibility than the body locations adopted in this experiment.

4.2. Participants

6 participants (aged 21 – 36 years; all male) volunteered to participate in our study. None of the participants have previous experience with under-clothing wearable devices. The participants were asked to wear a long sleeve shirt and a headphone to block the auditory perception caused by the vibration motor. Figure 7 shows the image of a participant during the experiment.

4.3. Procedure

The experiment required three hours to conduct per participant and was divided into two days, one hour and a half per day. For each day, trials with a single trial type, ascending or descending, were presented. Half of the participants were presented with the ascending trial on the first day, and the descending trial on the second day, while the other half of the participants were presented with the opposite order. The order of the 72 vibrations presented in a single day was randomized.

After the 10-minute explanation about the experiment's background and goal, informed consent was acquired from the participants. Participants were then instructed to put on the vibration devices in the designated locations of their bodies. The specific device locations for each participant were measured by the experiment conductor and informed to the participants before the device mounting phase. During the experiment, participants were also asked to wear a headphone with a high sound-insulating performance to avoid perceiving the actuating noise caused by vibration motors.

Participants will follow these steps in a single trial: (1) the vibrational stimulus presentation starts (2) push the Enter key when they notice a shift in the recognition state.

4.4. Results

The average of the obtained threshold value for each combination of the vibration type and body location is listed in Figure 8, and the values are written with the output voltage step of the microcomputer (0 to 255). The cell of the figure is painted with deeper color when the stimulus intensity value is low, meaning when the vibration types the cell represent is perceivable with lower intensity.

Two-way repeated-measures ANOVA was applied to the threshold value to determine which factors had significant effects on the scores. We observed that the rendering method ($F_{(3, 15)}$ =705.4, p< 0.001), duration time ($F_{(2, 10)}$ = 465.9, p <

Duration Time (s)

Rendering Methods	0.05	0.1	0.15
Linear	173.3	117.3	103.8
Log	161.5	107.1	89.2
Gaussian	135.0	97.7	80.4
Square	91.0	69.0	59.0

(Voltage steps out of 256 steps)

(a) Shoulder

Duration Time (s)

Rendering Methods	0.05	0.1	0.15
Linear	179.2	124.4	106.5
Log	166.3	117.1	99.0
Gaussian	143.8	100.4	87.9
Square	99.4	77.3	68.3

(Voltage steps out of 256 steps)

(b) Collarbone

Duration Time (s)

Rendering Methods	0.05	0.1	0.15
Linear	155.6	124.4	94.2
Log	136.7	103.1	90.2
Gaussian	124.0	89.2	79.8
Square	85.0	70.6	65.8

(Voltage steps out of 256 steps)

(c) Upper Arm

Figure 8: Threshold of each vibration type and body locations

0.001), and the interaction between them ($F_{(6, 30)}$ =28.6, p< 0.001) had significant effects on the threshold value. Also, the body location had a significant effect too ($F_{(2, 10)} = 9.4$, $p < 0.01$).

To further analyze the effects of each parameter, Ryan's method was applied to the average of the vibrational threshold. Though most threshold values of vibrations configuring the same rendering method ($Fs_{(2, 40)} > 8.0$, $ps < 0.01$) or the same duration time ($Fs_{(3, 45)} > 17.5$, $ps <$ 0.01) showed a significant difference with each other on the same body part, some of them did not. On the collarbone, there was no significant difference between the Linear-0.1 combination and Log-0.1 combination ($F_{(3, 45)} = 81.5$, $p < 0.05$), and Linear-0.15 combination and Log-0.15 combination ($F_{(3, 45)} = 51.3$, $p < 0.05$). On the upper arm, there was no significant difference between the Linear-0.15 combination and Log-0.15 combination ($F_{(3, 45)} = 17.5$, $p = 0.3597417$),

Table 5
Average effect size (Rendering Method)

Duration Time (s)	Effect Size
0.05	0.783
0.1	0.728
0.15	0.593

Table 6
Average effect size (Duration Time)

Rendering Method	Effect Size
Linear	0.815
Log	0766
Gaussian	0.741
Square	0.492

Gaussian-0.1 combination and Gaussian-0.15 combination ($F_{(2, 40)} = 43.291$, $p = 0.0681987$), and Square-0.1 combination and Square-0.15 combination ($F_{(2, 40)} = 8.0$, $p < 0.005$). The graphs of the threshold and the significant differences among them are shown in Appendix (a) to (g).

Table 5 shows the average effect size (η^2) of the rendering method for each duration time obtained from each body location. According to the values, the effect size declines at 0.15 by 0.19 from 0.05 and 0.135 from 0.1. Also, Table 6 shows the average effect size of the duration time for each rendering method obtained from each body location. The Square vibrations had the lowest effect size from the duration time. The effect size at Square declines by 0.323 from Linear, 0.274 from Log, and 0.249 from Gaussian.

4.5. Discussion

The results show that most types of vibrations consist of a unique threshold affected by the rendering method and duration time. From the results, the minimum intensity required to present a vibrational stimulus on the shoulder, collarbone, and upper arm was learned. These results would be a basis when designing vibrotactile under-clothing wearable applications e.g., attention guidance (AG) and obstacle avoidance (OA). In these applications, the intensity of the vibrational feedback could be designed regarding the priority and referring to the minimum perceivable intensity of each vibration type and its presenting location.

Also, the effect size differences are an element to discuss the features of the rendering methods and the duration times. The results show that the vibrations consisting of the Square rendering method were least affected by the duration time changes, and the vibrations consisting of 0.15 duration time were least affected by the rendering method type.

After the experiment, three out of six participants commented that they confused the presented vibration with their heartbeat around the intensity of their perceiving threshold. Previous studies investigate vibrational heartbeat's effect on human emotion [22], and the utilization of this method in VR experiences is being studied [23]. Regarding these comments and previous studies, the presentation of the vibrational heartbeat could be a possible application for the vibrotactile under-clothing wearable.

In this experiment, participants were seated and wore a headphone with high sound-insulating ability. However, the application of this device hypothetically contains a great amount of visual and audio stimulus which would possibly interfere with the device's vibrational stimulus, and the effects cannot be neglected. Regarding these factors, experiments with a more practical environment will be valid for further investigation of the vibrotactile under-clothing wearable's capability and the perceivable texture of the vibrations.

Participants were instructed to wear a thin shirt over an undershirt for this experiment to fasten the device with the magnets. This designation enabled the device to hold its position stably. However, not all users will be wearing light clothes in the conceivable applications. This indefinite condition of the user's garment could destabilize the device position, leading to a loss of vibrotactile feedback presentability. A further improvement of the device structure, such as the size and the type of magnet adopted in the device could be a countermeasure for this issue.

Table 7
Thresholds and the presented intensity steps for each vibration (Upper Arm)

	Linear	Log	Gaussian	Square
Threshold	135	128.75	111.25	95
Presented Step (0-255)	140	135	120	100

Table 8
Thresholds and the presented intensity steps for each vibration (Shoulder)

	Linear	Log
Threshold	138.75	131.25
Presented Step (0-255)	145	140

5. Mapping of the Vibration Texture

This experiment aims to map the vibration's texture features to physical features. By conducting this experiment, we aim to explore each vibration's feature perceived by the users to further investigate the aptitude for future applications.

5.1. Participants

The experiment was conducted with the cooperation of a human-computer interaction researcher, who is also one of this paper's authors. We conducted this experiment only with a researcher because it requires more training to classify varied types of haptic textures.

5.2. Settings

Five vibrations, Linear-0.1, Log-0.1, Gaussian-0.1, and Square-0.1, were presented to the upper arm, and two vibrations, Linear-0.1, Log-0.1, were presented to the shoulder. All the vibrations have a common duration time of 0.1, the second longest duration of the three adopted in the first experiment conducted in Chapter 4. The vibrations adopted in this experiment have an intensity that is five steps stronger than the participant's threshold of each vibration e.g., presented step 220 intensity for upper arm Gaussian-0.1 vibration which the threshold was 111.25, step 240 intensity for shoulder Log-0.1 vibration which the threshold was 131.25, and step 240 intensity for upper arm Linear-0.1 vibration which the threshold was 135. The thresholds and the presented steps are shown in Tables 7 and 8.

The locations were decided by testing each type of vibration on three locations, shoulder, collarbone, and upper arm. As a result of the comparison, there was no significant difference in the perceived texture between the collarbone and the other two locations, but there was a slight change in the upper arm and shoulder. At the two locations, the perceived textures of Linear-0.1, and Log-0.1 differed slightly, so the mapping was conducted separately.

The presented vibrations were mapped with 11 pairs of adjectives shown in Table 9. The participant was asked to choose a number between 1 through 7, which represents how accurately the presented vibration matches the adjective, while 1 and 7 are the extreme agreement with each adjective and 4 is neutral.

These adjectives were selected from two studies conducted by Strohmeier *et al*. [12] [21]. One study conducts a similar experiment as this, and the other presents adjectives obtained from participants' comments.

5.3. Procedure

The participant was presented with the vibrations and was instructed to choose a number between 1 and 7 for each pair of adjectives. The presentation order was random, and the participant was able to change the answers after perceiving other vibrations.

Table 9
The 11 pairs of adjectives

Smooth	-	Rough
Even	-	Bumpy
Blunt	-	Sharp
Light	-	Heavy
Slippery	-	Sticky
Soft	-	Hard
Quiet	-	Loud
Bad	-	Good
Dislike	-	Like
Weak	-	Strong
Passive	-	Aggressive

5.4. Result and Discussion

The result of the mapping is shown in Table 10. For the vibrations presented on the upper arm, Linear, Log, and Gaussian were evaluated to have a very similar texture in five out of 11 categories.

Table 11 shows the mean of the mapping result per adjective pair. Table 12 shows the difference from the mean of the mapping value of each pair of adjectives, and the sum of the difference for each rendering method. When looking at Table 12 it could be said that the most unique texture of the four is the Square with 10.50 points and followed by Log with 7.50 points.

For Linear and Log, the vibrations were presented to the shoulder too. Linear vibration on the shoulder presented a one-point weaker texture compared to the upper arm. The Log vibration on the shoulder presented a one-point lighter, harder, and two-point more aggressive texture than the upper arm. These results could be a basis for designing an application for the vibrotactile under-clothing wearable.

5.5. Conclusion

This paper proposes a vibrotactile under-clothing wearable to present vibrational feedback to the users of the contents with immersive technologies e.g., VR and MR. The

Table 10
Result of the mapping

	Upper Arm				Shoulder	
	Linear	Log	Gaussian	Square	Linear	Log
Smooth-Rough	2	4	2	3	2	4
Even-Bumpy	6	6	6	3	6	6
Blunt-Sharp	2	2	2	4	2	2
Light-Heavy	2	2	2	4	2	1
Slippery-Sticky	6	7	6	7	6	7
Soft-Hard	3	5	3	4	3	6
Quiet-Loud	5	5	5	3	5	5
Bad-Good	4	5	4	4	4	5
Dislike-Like	6	7	6	6	6	7
Weak-Strong	2	4	3	5	1	4
Passive-Aggressive	3	3	3	4	3	5

1	2	3	4	5	6	7

vibrations presented by our system are configured by four types of rendering methods and three lengths of duration times, resulting to gain the ability to present 12 types of unique vibrations. To investigate the texture feature of these vibrations, we have conducted two experiments, one to explore the stimulus threshold of each vibration on three body locations, and the other to map the perceived texture feature of the vibrations with multiple adjective pairs.

The first experiment showed the stimulus threshold of the 12 unique vibrations on three body locations, shoulder, collarbone, and upper arm. Most of the vibrations resulted to have a significantly different threshold value from each other, caused by both the rendering method and the duration time.

Table 11
Mean of the mapping result per adjective pairs (Upper Arm)

	Mean
Smooth-Rough	2.75
Even-Bumpy	5.25
Blunt-Sharp	2.50
Light-Heavy	2.50
Slippery-Sticky	6.50
Soft-Hard	3.75
Quiet-Loud	4.50
Bad-Good	4.25
Dislike-Like	6.25
Weak-Strong	3.50
Passive-Aggressive	3.25

The second experiment attempted to map the texture features of the vibrations by describing each vibration with 11 pairs of opposite adjectives. The results describe the feature of each vibration with numbers from 1 to 7 which shows the agreement score for each adjective. The Square rendering method appeared to be the most unique method, regarding the results of the average differences between the rendering methods.

The results of the two experiments will be a basis for designing the applications of the vibrotactile under-clothing wearable, such as the attention guidance and obstacle avoidance system for VR and MR. However, the stimulus threshold and the map of the textures gained from the experiments of this paper were gained under a certain condition with the participants seated and the visual and audio noises suppressed. Further study would be valid to investigate the effect of the environmental changes e.g., the participant's posture, visual and audio noises, and the designation of the participant's clothes.

Also, there was a comment from a participant that point out the difficulty of mounting the under-clothing wearable device by themselves. Hypothetically, this issue is caused by the large size and the low fastening capability. The downsizing and the enhancement of the fastening capability could be achieved by substituting the exterior with an original 3D-printed component, and magnets with a superior model.

Table 12
Difference from the mean of the mapping value of each pair of adjectives, and the sum of the difference (Upper Arm)

	Mean	Linear	Log	Gaussian	Square
Smooth-Rough	2.75	0.75	1.25	0.75	0.25
Even-Bumpy	5.25	0.75	0.75	0.75	2.25
Blunt-Sharp	2.50	0.50	0.50	0.50	1.50
Light-Heavy	2.50	0.50	0.50	0.50	1.50
Slippery-Sticky	6.50	0.50	0.50	0.50	0.50
Soft-Hard	3.75	0.75	1.25	0.75	0.25
Quiet-Loud	4.50	0.50	0.50	0.50	1.50
Bad-Good	4.25	0.25	0.75	0.25	0.25
Dislike-Like	6.25	0.25	0.75	0.25	0.25
Weak-Strong	3.50	1.50	0.50	0.50	1.50
Passive-Aggressive	3.25	0.25	0.25	0.25	0.75
Sum		6.50	7.50	5.50	10.50

References

[1] Jan Oliver Wallgrun, Mahda M. Bagher, Pejman Sajjadi, Alexander Klippel. A Comparison of Visual Attention Guiding Approaches for 360°Image-Based VR Tours. In *IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. 2020. DOI: 10.1109/VR46266.2020.00026

[2] Marco Speicher, Christoph Rosenberg, Donald Degraen, Florian Daiber, Antonio Krúger. Exploring Visual Guidance in 360-degree Videos. In *TVX '19: Proceedings of the 2019 ACM International Conference on Interactive Experiences for TV and Online Video*. June 2019. Pages 1-12. https://doi.org/10.1145/3317697.3323350

[3] Emanuele Nonino, Joy Gisler, Valentin Holzwarth, Christian Hirt, Andreas Kunz. Subtle Attention Guidance for Real Walking in Virtual Environments. In *2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*. 2021. DOI: 10.1109/ISMAR-Adjunct54149.2021.00070

[4] Fei Wu, Evan Suma Rosenberg, Andreas Kunz. Combining Dynamic Field of View Modification with Physical Obstacle Avoidance. In *IEEE Annual International Symposium Virtual Reality*. 2019. DOI: 10.1109/VR.2019.8798015

[5] Fabrizio Pece, Juan Jose Zarate, Velko Vechev, Nadine Besse, Olexandr Gudozhnik, Herbert Shea, Otmar Hilliges. MagTics: Flexible and Thin Form Factor Magnetic Actuators for Dynamic and Wearable Haptic Feedback. In *UIST '17: Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. October 2017. Pages 143–154. https://doi.org/10.1145/3126594.3126609

[6] Joao Bimbo, Claudio Pacchierotti, Marco Aggravi, Nikos Tsagarakis, Domenico Pratthichizzo. Teleoperation in cluttered environments using wearable haptic feedback. In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 24-28 September. 2017. DOI: 10.1109/IROS.2017.8206180

[7] Erik Pescara, Vincent Diener, Michael Beigl. VibrAid: Comparing Temporal and Spatial Tactile Cues in Control Room Environments. In *PETRA '19: Proceedings of the 12th ACM International Conference on PErvasive Technologies Related to Assistive Environments*. June 2019. Pages 138–145. https://doi.org/10.1145/3316782.3321531

[8] Ronan Hinchet, Velko Vechev, Herbert Shea, Otmar Hilliges. DextrES: Wearable Haptic Feedback for Grasping in VR via a Thin Form-Factor Electrostatic Brake. In *UIST '18: Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. October 2018. Pages 901–912. https://doi.org/10.1145/3242587.3242657

[9] Arpit Bhatia, Dhruv Kundu, Suyash Agarwal, Varnika Kairon, Aman Parnami. Soma-noti: Delivering Notifications Through Under-clothing Wearables. In *CHI '21: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. May 2021. Article No.: 221. Pages 1–8. https://doi.org/10.1145/3411764.3445123

[10] Mohammed Al-Sada, Keren Jiang, Shubhankar Ranade, Xinlei Piao, Thomas Höglund, Tatsuo Nakajima. HapticSerpent: A Wearable Haptic Feedback Robot for VR. In *CHI EA '18: Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. April 2018. Paper No.: LBW624. Pages 1–6. https://doi.org/10.1145/3170427.3188518

[11] Gyeore Yun, Seungjae Oh, Seungmoon Choi. Seamless Phantom Sensation Moving Across a Wide Range of Body. In *IEEE Robotics and Automation Letters*, 09-12 July. 2019. DOI: 10.1109/WHC.2019.8816104

[12] Paul Strohmeier, Kasper Hornbæk. Generating Haptic Textures with a Vibrotactile Actuator. In *CHI '17: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. May 2017. Pages 4994–5005. https://doi.org/10.1145/3025453.3025812

[13] Kosuke Nakagawa, Yasuyuki Okumura, Katsuyuki Fujii, Masahiro Umehira. Prototype Development of Vibration-induced Haptic Shoes for Perceiving the Front Obstacle. In *2021 IEEE 10th Global Conference on Consumer Electronics (GCCE)*. 12-15 October. 2021. DOI: 10.1109/GCCE53005.2021.9621908

[14] Ricky Jacob, Peter Mooney, Padraig Corcoran, Adam C. Winstanley. Haptic-GIS: exploring the possibilities. In *SIGSPATIAL Special, Volume 2, Issue 3*. November 2010.

pP23–18. https://doi.org/10.1145/1953102.1953105

[15] Zhenyu Liao, Jose V. Salazar Luces, Yasuhisa Hirata. Human Navigation Using Phantom Tactile Sensation Based Vibrotactile Feedback. In *IEEE Robotics and Automation Letters*, Vol. 5, No. 4. October. 2020. DOI: 10.1109/LRA.2020.3010447

[16] Zhiyong Xiong, Xinqi Huang. Comparison of the Static and Dynamic Vibrotactile Interactive Perception of Walking Navigation Assistants for Limited Vision People. In *IEEE Consumer Technology Society Section*. 2022. DOI: 10.1109/ACCESS.2022.3167407

[17] Gianluca Paolocci, Tommaso Lisini Baldi, Ludovico Sampieri, Domenico Prattichizzo. Design and Comparison of Haptic Policies for Human Guidance. In *2022 IEEE Haptics Symposium (HAPTICS)*. 2022. DOI: 978-1-6654-2029-7/22/$31.00

[18] Stefanie Schaack, George Chernyshov, Kirill Ragozin, Benjamin Tag, Roshan Peiris, Kai Kunze. Haptic Collar: Vibrotactile Feedback around the Neck for Guidance Applications. In *AH2019: Proceedings of the 10th Augmented Human International Conference 2019*. March 2019. Article No.: 12. Pages 1–4. https://doi.org/10.1145/3311823.3311840

[19] Kohei Kanamori, Nobuchika Sakata, Tomu Tominaga, Yoshinori Hijikata, Kensuke Harada, Kiyoshi Kiyokawa. Obstacle Avoidance Method in Real Space for Virtual Reality Immersion. In *2018 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 16-20 October. 2018. DOI: 10.1109/ISMAR.2018.00033

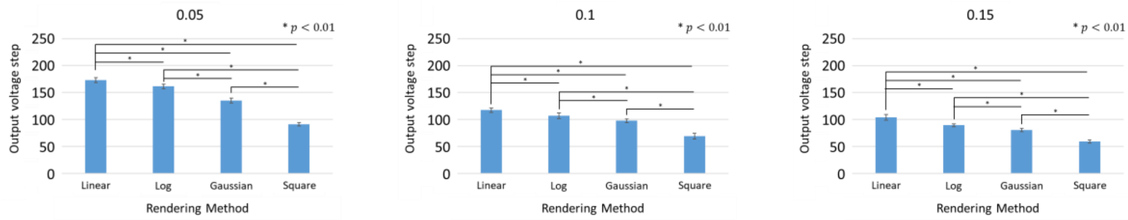
[20] Jaeeun Kim, Heeyoon Jeong, Gerard Jounghyun Kim. The Effect of 2D Stylized Visualization of the Real World for Obstacle Avoidance and Safety in Virtual Reality System Usage. In *VRST '21: Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*. December 2021. Article No.: 101. Pages 1–3. https://doi.org/10.1145/3489849.3489943

[21] Paul Strohmeier, Seref Güngör, Luis Herres, Dennis Gudea, Bruno Fruchard, Jürgen Steimle. The Effect of 2D Stylized Visualization of the Real World for Obstacle Avoidance and Safety in Virtual Reality System Usage. In *UIST '20: Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*. October 2020. Pages 579–593. https://doi.org/10.1145/3379337.3415828

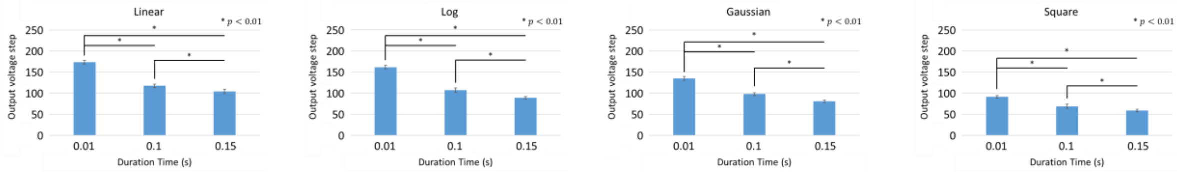
[22] Yizhen Zhou, Aiko Murata, Junji Watanabe. The Calming Effect of Heartbeat Vibration. In *2020 IEEE Haptics Symposium (HAPTICS)*. 28-31 March 2020. https://doi.org/10.1109/HAPTICS45997.2020.ras.HAP00.157.5a2e1551

[23] Dennis Wolf, Michael Rietzler, Leo Hnatek, Enrico Rukzio. Face/On: Multi-Modal Haptic Feedback for Head-Mounted Displays in Virtual Reality. In *IEEE Transactions on Visualization and Computer Graphics (Volume: 25, Issue: 11, November 2019)*. 12 August 2019. https://doi.org/10.1109/TVCG.2019.2932215

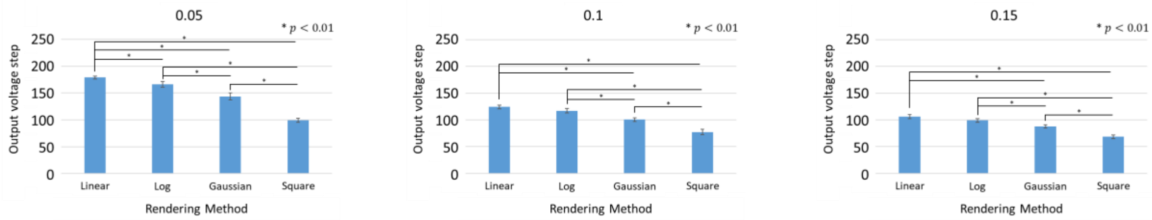
Appendix



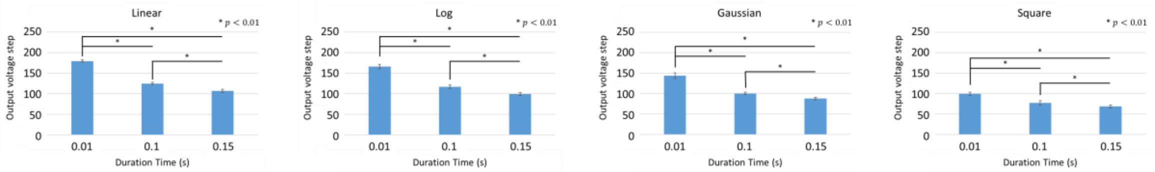
(a): Thresholds analysis by Duration Time (Shoulder)



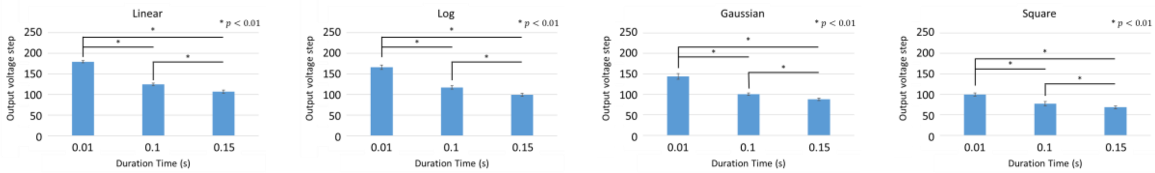
(b): Thresholds analysis by Rendering Method (Shoulder)



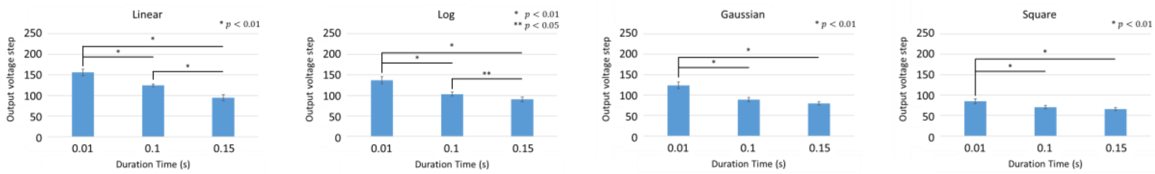
(c): Thresholds analysis by Duration Time (Collar Bone)



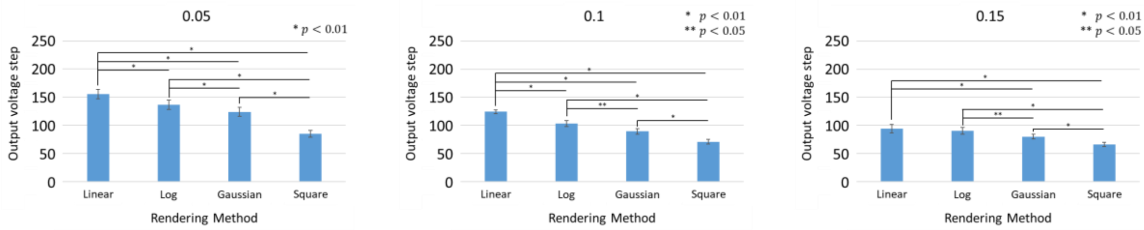
(d): Thresholds analysis by Rendering Method (Collar Bone)



(e): Thresholds analysis by Rendering Method (Collar Bone)



(f): Thresholds analysis by Rendering Method (Upper Arm)



(g): Thresholds analysis by Duration Time (Upper Arm)