BRILL
Multisensory Research 39 (2026) 379–398
MULTISENSORY RESEARCH
brill.com/msr

Pseudo-Dribbling Experience Using Single Overlapped Vibrotactile Stimulation Simultaneously to the Hand and the Feet

Takumi Kuhara [1,*], **Kakagu Komazaki** [2], **Junji Watanabe** [2] **and Yoshihiro Tanaka** [1,3]
[1] Nagoya Institute of Technology, Nagoya, Japan
[2] NTT Communication Science Laboratory, Atsugi, Japan
[3] Inamori Research Institute of Science, Kyoto, Japan
[*]Corresponding author; e-mail: t.kuhara.538@nitech.jp
ORCID iDs: Kuhara: 0009-0002-3966-2346; Komazaki: 0009-0005-9616-4249;
Watanabe: 0000-0001-6813-8004; Tanaka: 0000-0001-7917-1379

Received 31 December 2024; accepted 13 August 2025; published online 24 September 2025;
published in print 1 April 2026

Abstract
When designing a haptic interface, simplicity is crucial to avoid negative effects caused by excessive weight and complexity. Using multimodal information, haptic illusions, and providing context are known to create simpler interfaces. We have previously proposed the use of single overlapped vibrotactile stimulation (SOVS) for presenting spatiotemporal tactile perception, a method that simultaneously presents overlapped waveforms to multiple body parts. There, the acceleration measured from a person dribbling a basketball with an accelerometer positioned on the index finger and the floor was overlapped to present as stimuli. When the stimuli were presented simultaneously to the hand and the feet, it demonstrated a dribbling sensation, like an imaginary ball moving back and forth between the hand and the feet. This demonstrated the potential to eliminate the need for time synchronization and reduce the number of required channels, ultimately leading to the development of simple haptic interfaces that enhance an immersive experience. In this paper, we aim to investigate the key factor behind the perception of SOVS using simple vibrotactile stimuli. The first experiment measured the occurrence rate of the dribbling feeling for different combinations of prepared stimuli, and the results show that the combination of two different input amplitudes is crucial for the occurrence rate of the phenomenon. The second experiment assessed how realistic each stimulus, presented to the hand and the feet separately, felt to the participants. The results show that for the hand, the perceived reality corresponded to the strength of input amplitude, whereas the second-strongest input amplitude was perceived as most realistic for the feet. This suggests that when the combination consists of duplicate input amplitudes and/or those with low perceived reality, the occurrence rate tends to decrease.

Published with license by Koninklijke Brill BV | DOI: 10.1163/22134808-bja10157

ISSN: 2213-4794 (print) 2213-4808 (online)

Keywords
vibrotactile stimulation, tactile perception, single overlapped vibrotactile stimulation, multimodal

1. Introduction

Advancements in haptic technology have facilitated the adoption of haptic stimuli, which are currently being explored and developed. These advances have the potential to enhance experiences and performance in areas such as manufacturing, medicine, rehabilitation, entertainment, and skill training. Numerous studies have demonstrated that haptic stimuli improve immersion (Sallnäs, 2010) and task performance (Galambos, 2012; O'Malley *et al.*, 2006). For example, integrating haptic information such as texture and force with visual information enhances immersion and the sense of presence in virtual reality (Achibet *et al.*, 2015; Shirota *et al.*, 2019), enabling users to feel as if they are interacting with a digital object (Wee *et al.*, 2021). In 2D navigation, vibrotactile feedback for directional guidance has significantly improved performance (Jeon *et al.*, 2013). Presenting music as vibrotactile stimuli to areas like the collarbone (Sakuragi *et al.*, 2015) or upper body (Yamazaki *et al.*, 2016) can also increase the immersion of music listening experiences.

Despite these benefits, the adoption of haptic stimuli can also present limitations that interfere with the experience. The implementation of haptic stimuli often requires actuators to interact with a person's body or environment physically. This can be inconvenient from the perspective of the disturbance of perception and efficiency due to the excessive weight, physical contact, and complexity of the interface (Yao *et al.*, 2024). In addition, delivering stimuli to different parts of the body requires multiple channels, which often increase the number of connected cables to the interface as well as the weight and number of physical interactions. These can restrict the degree of freedom, limiting the user's mobility, which is known to be crucial for immersion (Mott *et al.*, 2020). Yan *et al.* (2019) reported that stimulus timing is also critical across different modalities. Thus, it is crucial to keep the interface design as simple as possible to avoid negative effects caused by these limitations.

One example of an effective approach to achieving simpler designs for haptic stimuli is leveraging principles of human perception. Understanding how humans perceive sensory information through dominant cues can enable simpler and more efficient interface designs. For example, applying lateral force feedback has been demonstrated to simulate a bumping feeling (Robles-De-La-Torre and Hayward, 2001). This innovation has not only improved the rendering for vibrotactile stimulation but also advanced surface haptics by enabling the presentation of texture and roughness on physical surfaces like touchscreens. This study allowed the elimination of the need for vertical movement and has enabled thinner designs in interfaces (Kim *et al.*, 2022). In addition to leveraging principles of human perception, haptic illusory phenomena can also be useful to simplify interfaces. For example, there are phantom sensations (Kato *et al.*, 2010) and tactile apparent motion (Hachisu and Suzuki, 2018). The phantom sensation creates the illusion of stimulus location, allowing people to feel a haptic perception at a location without physical interaction. Tactile apparent motion can generate a sensation of movement across multiple body parts using several fixed actuators. As another example of a phenomenon where the actuator numbers do not align with the perceived feeling is Geldard's cutaneous rabbit illusion (Geldard and Sherrick, 1972). This illusion is evoked by tapping two or more parts of the arm to create the sensation of taps hopping up the arm, even to places without any physical interaction. These phenomena indicate that haptic illusory phenomena can cause people to perceive discrete mechanical stimuli as a continuous movement of an object, which shows the possibility of reducing the number of actuators required to present a particular moving feeling.

Additionally, presenting multimodal information and context can significantly influence sensory perception and cognition. Prior studies have shown that vibrotactile stimuli combined with auditory stimuli can modify perceptions of intensity (Won and Altinsoy, 2020), roughness, and density (Kim *et al.*, 2007). This indicates that multimodal information has the potential to convey experiences that surpass the physical limitations of mechanical stimuli. A compelling example of leveraging multimodal information is the creation of pseudo-haptic sensations using sensory inputs besides haptic stimuli. When body movements and visual or auditory stimuli output are misaligned, pseudo-haptic feedback can be simulated by manipulating graphical responses based on user input. For instance, Paljic *et al.* (2004) and Lecuyer *et al.* (2000) demonstrated this by altering the motion response of a visual element, creating an illusional force feedback. Contextual cues also significantly enhance haptic experiences. For example, Hayward and MacLean (2007) demonstrated that moving a bar with a vibrotactile actuator back and forth could create the illusion of a ball moving inside the bar. Similarly, the Techtile Toolkit also showed that watching marbles fall into a cup while feeling vibrations recorded through a microphone under the cup could make users perceive they were holding a cup being filled with marbles, even when the cup was empty (Minamizawa *et al.*, 2012). In mental imagery (MI), various MI modalities — such as visual, auditory, and tactile — can activate the corresponding sensory cortices (Nierhaus *et al.*, 2023). These examples suggest that contextual cues, including individual images, can potentially impact sensory perception across different modalities to substitute the options, such as increasing the number of actuators, dynamically moving the actuators in response to motion, or precise motion tracking.

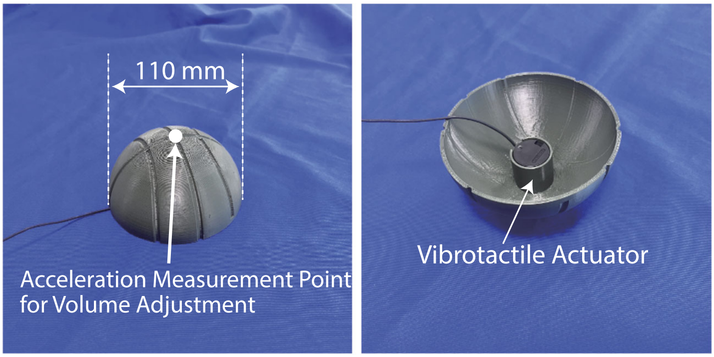

Figure 1. Handheld device used in the presentation system, designed to resemble a basketball, features a 5 mm groove. The vibrator is positioned behind the top to ensure even vibration distribution throughout the device, and the white point on the top is where we measured the acceleration of each adopted stimulus to adjust the amplitude volume throughout the experiment in advance. The accelerometer was taken off and was not measured during the experiment.

Our previous study demonstrated a pseudo-dribbling basketball experience using single overlapped vibrotactile stimulation (SOVS) (Kuhara *et al.*, 2023). We measured acceleration of a person dribbling a basketball using an acceleration sensor positioned on the index finger and the floor. We overlapped the two vibrations and presented them simultaneously to both the hand and feet through a specific device. The experimental results revealed that even when the same information was presented simultaneously to the hand and feet, participants experienced a dribbling sensation akin to an imaginary ball moving alternately between them. Additionally, we found that the direction of attention influenced the phenomenon, suggesting that the individual's mental image of a basketball dribble also plays a role. The use of SOVS helps mitigate issues related to time synchronization when presenting stimuli to multiple body parts and reduces the number of channels required to create coordinated sensations across different locations. Thus, the main goal of this research is to elicit the critical factors for the pseudo-dribbling experience using SOVS. In this paper, we investigated the potential of inducing this pseudo-dribbling phenomenon with simple vibrotactile stimuli by conducting two experiments, each focusing primarily on intensity and reality to reveal the relationships between the phenomenon's occurrence.

2. Presentation System

We used the pseudo-dribbling system from our previous study (Kuhara *et al.*, 2023). The system consists of a handheld device and footwear devices, as shown in Figs 1 and 2. Each device was designed to resemble the structure

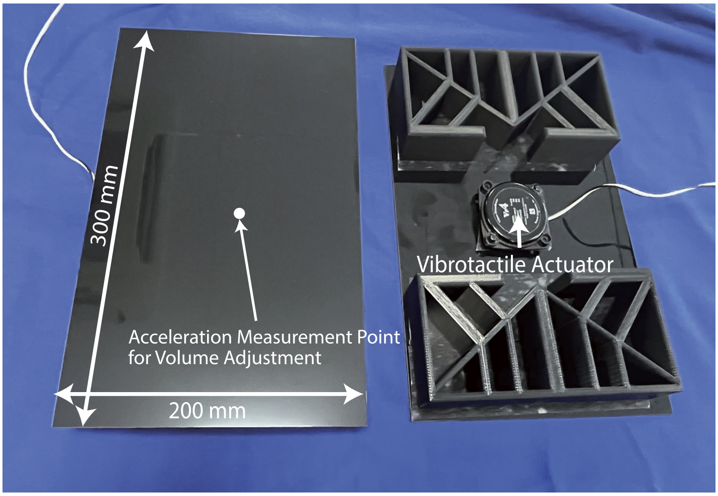

Figure 2. Footwear devices used for the presentation system; the supporting legs made of ASA had a height of 80 mm. The white point on the top is where we measured the acceleration of each adopted stimulus to adjust the amplitude volume throughout the experiment in advance. The accelerometer was taken off and wasn't measured during the experiment.

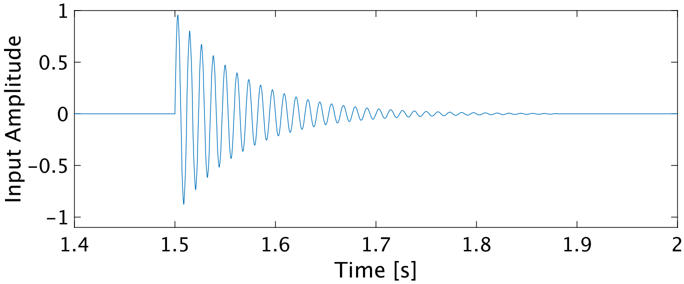

Figure 3. An example of the created stimulus (S5): a decaying 85 Hz sinusoidal with a duration 0.35 s and input amplitude of 1.0.

of a basketball and the gymnasium floor, with a vibrotactile actuator (Foster, 639897 & Acouve Lab., VP4) in each, used to present the stimuli. The amplitude of both devices was adjusted to output the same acceleration when presenting the same stimulus. The handheld device is a half-sphere with a diameter of 110 mm and a thickness of 2 mm, 3D-printed using acrylonitrite styrene acrylate (ASA). It is designed to be comfortably held by an adult with one hand. The footwear devices were an acrylonitrile butadiene styrene (ABS) plate measuring 300 × 200 × 1.5 mm, with supporting legs printed with ASA material, capable of holding the weight of an adult.

We prepared five stimuli (S1, S2, S3, S4 and S5) for the experiments, each providing different intensities using the same vibration waveform. Figure 3 shows an example of the adopted waveform. We used a constant sinusoidal wave multiplied by an exponential decay for the waveform, as given by

$$y = \sin(2\pi f t)\mathrm{e}^{(-15t)} \tag{1}$$

where the frequency f is 85 Hz, and t represents time. Each waveform was generated at a sampling frequency of 10 kHz with a duration of 0.35 s. In many situations where people try to present impacts, decaying waveforms are well-used (Hachisu *et al.*, 2011). Thus, we also adopted an exponentially decaying sinusoidal wave to present the impact of the basketball hitting the hand and the floor. The adopted parameters of the waveform were chosen based on preliminary experiments that found it produced the most ballbouncing-like texture. With 1.0 as the maximum input amplitude due to the limit of the output device, the five intensity levels were determined using the maximum input amplitude of 0.2 (S1), 0.4 (S2), 0.6 (S3), 0.8 (S4) and 1.0 (S5), corresponding to maximum accelerations of 37, 39, 41, 43 and 45 $\mathrm{m/s^2}$, respectively. The acceleration of each intensity level was measured in advance to adjust the amplifier's volume so the stimuli presented to the hand and the feet had the same amplitude, although using different vibrotactile actuators.

3. Methods

3.1. Participants

We conducted two experiments to identify the combination of conditions that induce a dribbling sensation when presenting SOVS. Thirty participants (23 male and seven female; 28 right-handed and two left-handed) participated in all experiments, with an honorarium of 1050 JPY (approximately 7.2 USD). The participants were first asked to complete a questionnaire to determine their dominant hand (Coren, 1992). The experiments were conducted in accordance with the Declaration of Helsinki and were approved by the Ethics Committee of Nagoya Institute of Technology (2021-8).

Each participant was informed in advance about the purpose of the experiment, the method used, and the phenomenon they were expected to perceive: "During the experiment, we will present multiple vibrotactile stimuli to your hands and feet using handheld and footwear devices. The stimulus presented to your hands and feet will be the same vibration throughout the experiment. However, at times, you may experience the sensation of an imaginary ball moving up and down between your hands and feet. The goal of these experiments is to investigate whether this phenomenon is consistent across individuals and to determine the conditions needed to elicit this specific sensation".

After the explanation, the participants were asked to hold the handheld device with their dominant hand and step on the footwear devices with each

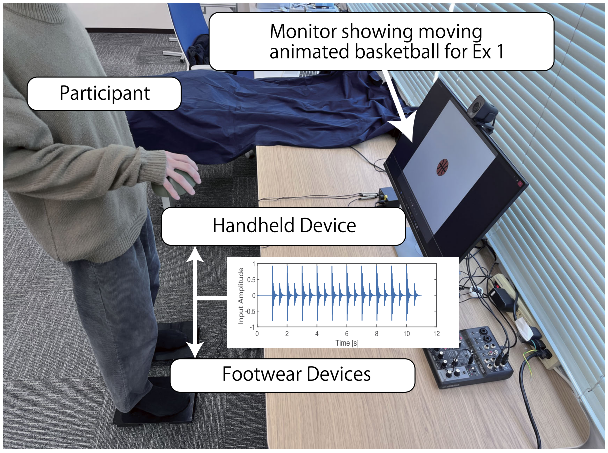

Figure 4. Experimental environment: The participants had a monitor showing an animated basketball moving up and down in front of them for experiment 1 and showed a black screen for experiment 2. For the posture throughout the experiment, all of the participants were asked to hold the handheld device with their dominant hand in front of their body and step on the footwear devices with their socks on. Both the handheld device and footwear devices presented the same stimulus simultaneously.

foot. They were also instructed about their posture throughout the experiment. Figure 4 shows the experimental environment and the posture the participants were instructed to hold. The participants had a monitor in front of them and were instructed to stand straight, with the hand holding the handheld device positioned in front of their body. Additionally, it was explained that if they felt the handheld device slipping and thought they might drop it during the experiment, they were allowed to hold onto the edges of the device using their thumbs or pinky fingers.

3.2. Experiment 1: Intensity Combination

For the first experiment, we tested whether the intensity difference of the combination presented as SOVS could induce the pseudo-dribbling phenomenon. The intensity of a vibrotactile stimulus is known to affect the experience directly (Bochereau *et al.*, 2014). We believed it is possible to explore the principles related to the dribbling phenomenon using the adopted simple waveforms of a decaying 85-Hz sinusoidal wave. During the preliminary experiment, we found that the bouncing feeling also decreased when the amplitude of the adopted stimuli was low. Thus, we hypothesized that the intensity is also an important factor for the pseudo-dribbling phenomenon that occurs using SOVS. Figure 5 shows two examples of a combination presented as SOVS. For each combination, one of the created stimuli overlapped (S1, S2, S3, S4 and S5) with another that was delayed by 0.5 s. All combinations were designed so

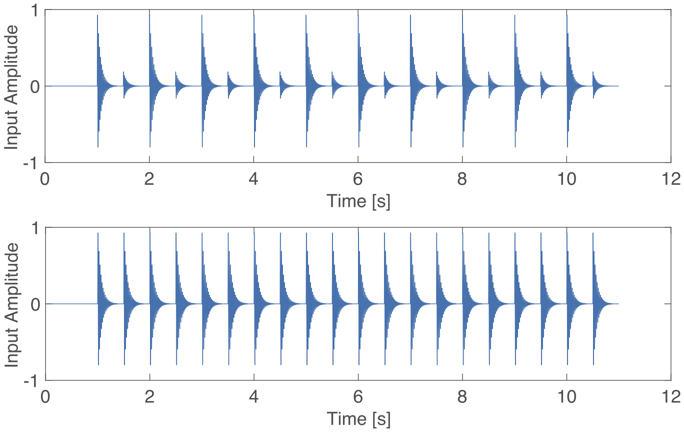

Figure 5. Two examples of combinations used as SOVS: (Top) S1–S5, which combines S1 and 0.5 s delayed S5; (bottom) S5–S5, which combines stimulus 5 and a 0.5 s delayed S5.

Table 1.
Combination of stimuli for SOVS

Overlapped stimulus	0.5 s delayed stimulus (input max. amplitude)				
	S1 (0.2)	S2 (0.4)	S3 (0.6)	S4 (0.8)	S5 (1.0)
S1 (0.2)	S1–S1				
S2 (0.4)	S2–S1	S2–S2			
S3 (0.6)	S3–S1	S3–S2	S3–S3		
S4 (0.8)	S4–S1	S4–S2	S4–S3	S4–S4	
S1 (1.0)	S5–S1	S5–S2	S5–S3	S5–S4	S5–S5

that the first stimulus was presented for 0.0 to 0.35 s and the second stimulus for 0.5 to 0.85 s, and would repeat every second. The overlapped combination was presented 10 times repeatedly, totaling 20 vibrations, with the entire sequence completed in approximately 11 s. We overlapped all combinations of the created five stimuli, excluding the already tested combinations, resulting in a total of 15 combinations, as shown in Table 1. The prepared combinations were presented once, randomly, to minimize the effects of stress and fatigue during the experiment.

During our preliminary experiment, we found that some combinations produced a dribbling sensation that was approximately twice as fast as the expected dribbling feeling. To evaluate whether the participants experienced the desired dribbling sensation, during the experiment we presented, on a monitor in front of them, an animated basketball moving up and down at a frequency of 1 Hz as shown in Fig. 6, which was consistent with a tactile stimulus

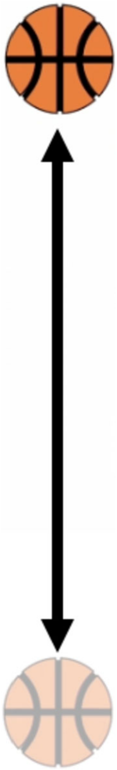

Figure 6. Presented animation of dribbling. The ball, depicted as a circle with a diameter of 55 mm, moved up and down for a distance of 170 mm on the monitor in front of the participants.

of a single stimulus presented alternately to the hand and the feet. To reduce the influence of visual context, the animation was not synchronized with the vibrotactile stimuli, and the participants were not instructed on when to view the animation. The animation of the basketball enabled a comparison between the perceived feeling and the expected dribbling sensation. After each stimulus presentation, the participants were asked whether they felt the speed of the imaginary ball's dribbling movement was the same as that of the animated basketball moving up and down in front of them during the experiment. The participants were instructed to answer 'Yes' only when they felt the dribbling sensation and the speeds of the imaginary and animated balls were similar. If the participants did not feel the dribbling sensation or the movement speed differed from that of the animated basketball, they were instructed to answer 'No'. From the responses of all participants, an occurrence rate was calculated for each combination.

For the data collected from the first experiment, we conducted a binomial test for each answer and applied a Bonferroni correction to determine whether the answers were statistically significant against the chance level (0.5). Furthermore, to assess whether the intensity of the overlapped vibrotactile stimuli represents the pseudo-dribbling phenomenon, we conducted a multiple-regression analysis represented by

$$Z = a(x - y)^2 + b(x + y)^2 + c \tag{2}$$

where Z represents the occurrence rate of the phenomenon, and a, b and c are the coefficients for each factor, with x and y representing each stimulus's overlapped intensity levels (peak acceleration). We adopted equation (2) because previous studies have shown that the perceived vibrotactile intensity correlates with the power spectrum (Bensmaïa *et al.*, 2005) and absorbed power (Hwang *et al.*, 2013). Since the stimulus involved only one frequency component, the power spectrum and waveform energy, derived from the time domain, can be calculated as the square of the waveform using Parseval's theorem. To differentiate the overlapping vibrotactile stimuli, we hypothesized that both the intensity difference and the overall intensity would be critical factors. Consequently, we used $(x - y)^2$ and $(x + y)^2$ in the regression model. To assess the accuracy of this model, we conducted an analysis of variance (ANOVA).

3.3. Experiment 2: Effect of Reality

In the second experiment, we evaluated the order of reality for the five stimuli created to investigate the relationship between the occurrence of the phenomenon. Experiment 1 was conducted first, followed by experiment 2 because asking about the reality first might induce an impression bias — where participants associate a high reality with the feeling of dribbling, thus potentially affecting their evaluations — and since the factors underlying the dribbling experience remain unclear, participants were first asked to assess whether or not they experienced the dribbling sensation in experiment 1. For experiment 2, each stimulus was presented three times, with a 0.5-s silent interval between each presentation. The stimuli were presented in a random order. The experiment was controlled *via* a graphical user interface (GUI), as shown in Fig. 7. After each stimulus was presented in each trial, participants were asked to rank the order of realism for each stimulus. This method was conducted for both the hand and the feet separately, and the starting order for evaluation on the hand or the feet was counterbalanced among participants.

Participants were asked to rank the stimuli using the following method: first, the first and second stimuli shown on the GUI, anonymized in a random order, were presented, and participants were asked which stimulus felt more realistic. Participants were asked to imagine a ball hitting their hand during a

Figure 7. GUI for experiment 2: The experimenter inputted all answers, and the GUI was displayed to the participants to ensure their responses were recorded.

basketball dribble for the stimulus presented to the hand, imagine a ball hitting the gym floor for the stimulus presented to the feet, and compare their image with the presented stimuli. After the participants answered which stimulus was more realistic, the third stimulus was then presented, and participants ranked the third stimulus in terms of reality. The same procedure was followed for the fourth and fifth stimuli. Responses were recorded using the GUI. After the participants had ranked all five stimuli, each stimulus was presented again in the order of the answered rank of reality to allow participants to ensure their answers. After reviewing their answers, participants were asked if they would like to change their rankings. If they answered ‘yes’, adjustments were made before recording the final rankings; if not, the answers were recorded as provided.

For the second experiment, we conducted a Friedman test to assess differences in perceived reality across the five stimuli. When a significant difference was found, the Wilcoxon signed-rank test with Bonferroni correction was applied for *post-hoc* multiple comparisons.

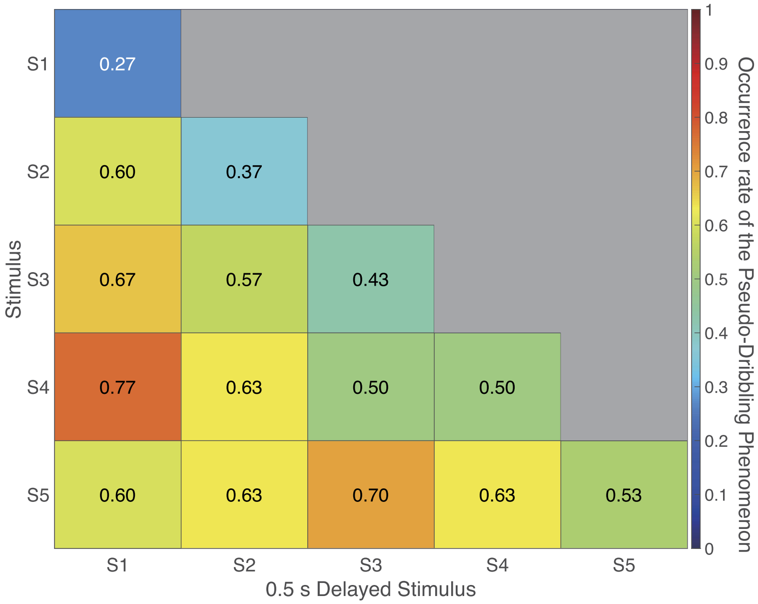

Figure 8. A heatmap showing the occurrence rate of the pseudo-dribbling phenomenon; the number in each cell represents the occurrence rate calculated for each stimulus, and the upper-right corner displays the combinations already implemented, which were excluded from experiment 1.

4. Results

4.1. Intensity Combination

The results of experiment 1 are shown in Fig. 8 as a heatmap. The horizontal and vertical axes represent the combined stimulus, and each cell represents the combination of the horizontal and vertical stimulus. Each number inside the cell indicates the probability of a ‘Yes’ answer for each combination. The results show that the combination S1–S4 had the highest probability of 0.77, while the duplicate combination S1–S1 had the lowest probability of 0.27. These results suggest that different stimulus combinations influence the occurrence rate of the pseudo-dribbling phenomenon. The binomial test with Bonferroni correction against the chance rate (0.5) revealed a significant tendency of a high occurrence rate with the combination of S1–S4 (adj. $p = 0.078$), and the duplicate combination S1–S1 showed a significant low tendency in the occurrence rate (adj. $p = 0.078$).

For the multiple-regression model, the coefficient values were obtained, and the model is represented as follows:

$$Z = 0.014(x - y)^2 - 0.002(x + y)^2 + 0.58 \tag{3}$$

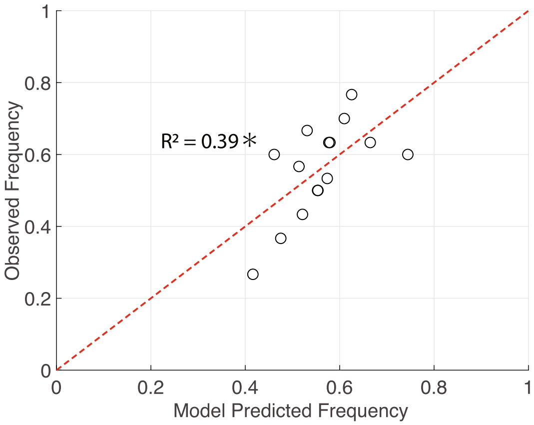

Figure 9. Regression model of the occurrence rate of the pseudo-dribbling phenomenon: the relationship between the predicted occurrence frequency and the observed occurrence frequency is shown as a scatter plot, and the red dotted line is shown as an ideal relationship with the coefficient of determination R^2 shown on the top left ($*p < 0.05$).

The relationship between the estimated value from the model and the measured actual value is shown in Fig. 9. The ANOVA results indicated that the regression model in equation (3) was statistically significant ($F_{2,12} = 3.90$, $p = 0.049$), with a coefficient of determination of 0.39. The results indicate that both a larger difference in intensity and a combined intensity of two overlapping stimulations contribute to inducing a stronger perceptual effect.

4.2. Effect of Reality

The results of the second experiment are shown in Fig. 10 as a boxplot. The top half shows the responses to the stimuli presented to the hand, and the bottom half shows the responses to the stimuli presented to the feet. For the stimuli presented to the hand, S1 was ranked as the least realistic. Similarly, for the stimuli presented to the feet, S1 was also ranked as the least realistic, but there was more variance in the responses compared to the hand. The stimuli that were evaluated as having the highest reality on average were S5 for the hand and S3 for the feet. The results of the Friedman test showed a significant difference in both conditions for the hand (${\chi^2}_4 = 48.13$, $p < 0.001$) and the feet (${\chi^2}_4 = 48.13$, $p < 0.001$). *Post-hoc* multiple comparisons, using the Wilcoxon signed-rank test with Bonferroni correction, revealed a significant difference between the responses to S2–S5 and S1 for the hand (S2–S5 compared to S1 all showed adj. $p < 0.001$). For the feet, *post-hoc* multiple comparisons showed a significant difference between S2–S4 and S1 (S2–S1: adj. $p = 0.020$, S3–S1: adj. $p < 0.001$; S4–S1: adj. $p = 0.017$) and a significant tendency between S1 and S5 (adj. $p = 0.055$).

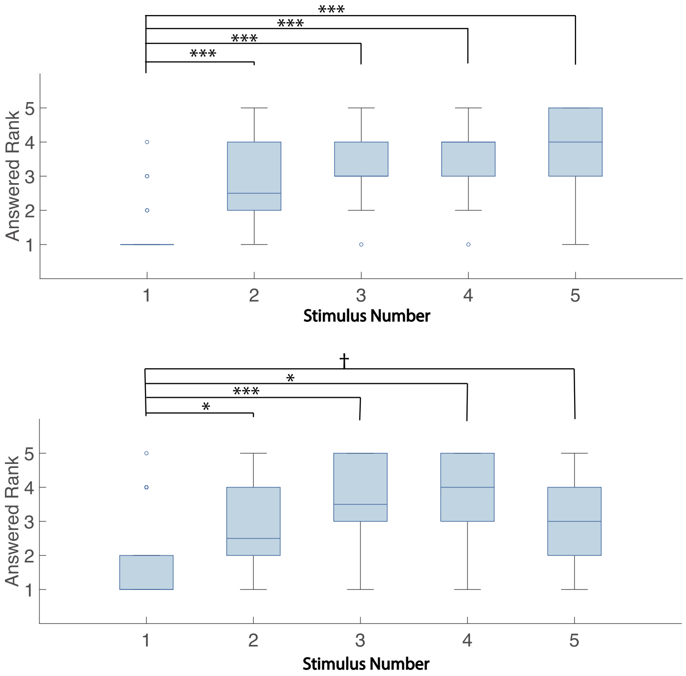

Figure 10. Boxplot of the perceived reality rankings; the top plot represents the answers for the hand, and the bottom plot represents the answers for the feet. (***$p < 0.001$; *$p < 0.05$; $^{\dagger}p < 0.1$).

5. Discussion

The results from experiment 2 suggest that S1 was perceived as the least realistic for both the hand and the feet, which may have been affected by the difference between the predicted intensity from the image of dribbling and the perceived intensity. The results also indicate that the hand has a broader range of acceptable intensity, while the feet have a relatively narrower range. For the hand, S2–S5 showed a significant difference from S1, and for the feet, S2–S4 showed a significant difference from S1. Before the experiment, we instructed participants to imagine dribbling a basketball on a gymnasium floor. When dribbling, many people likely imagine the vibration of the basketball hitting their hand and the vibration from the ball hitting the floor *via* their shoes. It seems that participants expected a stronger vibration in the hand than in the feet. Furthermore, the vibration perceived by the hand during dribbling is a consequence of active touch, where we can control how we hit the ball, which may allow a wider range of intensity. In contrast, the feet experience passive touch, which cannot be controlled much compared to the hand. This difference may have affected the prediction of perceived intensity, resulting in the difference in the acceptable range of intensity for the hand and feet.

The results from experiment 1 demonstrated that the combination of stimuli with different input amplitudes used for SOVS influences the occurrence rate of the pseudo-dribbling phenomenon. The heatmap in Fig. 8 shows that the occurrence rate of the pseudo-dribbling feeling varies but is consistently over the chance level of 0.5 when different input amplitude levels are combined. This indicates that for SOVS, overlapping two stimuli with different amplitudes can elicit the pseudo-dribbling phenomenon. The result shown in Fig. 8 showed that when the input amplitude difference was high, the occurrence rate of the phenomenon also tended to be high. In contrast, the duplicate stimulation showed a weak occurrence rate. The multiple-regression results supported this tendency, representing $(x - y)^2$ had a positive coefficient. This indicates the potential for discrimination between the overlapping vibrotactile stimuli. SOVS induces a dribbling sensation similar to that generated by presenting two vibrotactile stimuli alternately to the hand and feet. This suggests users optimize two vibrations and localize them as stimuli for both the hand and the feet, which makes the pseudo-dribbling phenomenon happen. To achieve this, the two vibrotactile stimuli must be distinguishable to aid in cognitive separation. This implies that duplicate combinations are unsuitable for SOVS, as it becomes harder to discriminate the overlapping vibrotactile stimuli on each of the hand and the feet.

However, the combination S1–S5, which held the greatest difference in input amplitude, did not yield the highest occurrence rate. The multiple-regression model consisted of two factors: the difference in input amplitude and the overall strength of the input amplitude. Although the coefficient of $(x + y)^2$ was smaller than that of $(x - y)^2$, this suggests that the overall strength of the stimulus may have influenced the occurrence of the pseudo-dribbling phenomenon. Additionally, the occurrence rate for duplicate combinations is lower than for different combinations; however, it tends to increase relative to the strength of intensity. The results of experiment 2 imply the contribution of reality. The reason the combination S1–S5 did not yield the highest occurrence rate may be related to the degree of reality. S5 lacked high realism for the feet, and S1 exhibited significantly lower realism compared to the other stimuli for both the hand and feet. As a result, the overall realism presented may have been low and potentially unacceptable. Considering both the multiple-regression model and the results from experiment 2, it is consistent that the combinations with a high degree of reality and perceivable differences in intensity — such as combination S3–S5, S4–S5, and S2–S4 — had relatively high occurrence rates (greater than 63%). This supports that reality is another critical factor for the occurrence of the pseudo-dribbling phenomenon. Here, the results from experiment 2 revealed that S2–S4 showed a significant difference compared to S1 in the order of reality for both the hand and feet. This provides an expectation that the combination S2–S4 could have the highest occurrence rate. However, the experiment results showed that the combination S1–S4 had the highest occurrence rate. This suggests that perceptual contrast may outweigh perceived realism in triggering the illusion. S2–S4 showed a significant difference from S1, indicating that S1 was discriminable in both intensity and reality. Individual differences may also have influenced the occurrence rate of the pseudo-dribbling phenomenon. Prior studies (Kuhara *et al.*, 2023) have demonstrated that the experience in basketball and the direction of attention influence the perception of dribbling throughout stimulus presentation. However, we did not control for these factors in the experiment conducted for this paper, which may have affected the occurrence rate beyond the combination of input amplitudes and perceived reality.

Finally, we address the limitations encountered during the experiment. Since the stronger intensity of the two overlapped stimuli was always presented first for the adopted combination of stimuli, we did not consider the order of the overlapping combination presented as SOVS. Dribbling a basketball generally starts with hitting the ball with the hand. If the vibration at the hand is greater than the vibration at the feet, this order would align with the person's mental image. Taking into account the image, the order of the intensity may influence the occurrence rate. Therefore, we need to investigate the occurrence rate of the pseudo-dribbling phenomenon when changing the order of overlapping and presenting the weaker stimuli first. Additionally, we did not consider the participants' experience of dribbling a basketball inside a gymnasium. This experience likely influenced the mental image the participants held during the experiment. Previous studies conducted by Kuhara *et al.* (2023) have demonstrated that the dribbling sensation decreases when the mental image is disrupted. For the visual sensation, it is known that people can compensate for missing sensory information using imagination based on memory (Cao *et al.*, 2020). This indicates that the variation in the mental image held by the participants could have affected the prediction of the stimuli, thereby influencing the occurrence rate of the pseudo-dribbling phenomenon by SOVS.

The results of this study demonstrate the potential of providing tactile apparent motion across multiple parts of the body using SOVS. From these results, the usage of SOVS has the potential to present various movements of objects around the body without the need for multiple channels and time synchronization. For example, SOVS may help present experiences of sports that utilize the whole body and tasks that require both hands, such as soccer, fencing, or other sports where multiple tactile stimuli are expected to occur. This approach reduces the complexity associated with time synchronization and the fixation of actuators, enabling a simple way to evoke a sense of movement from imaginary objects around the body. Furthermore, the findings have the potential to offer insights into spatiotemporal tactile perception when presenting multimodal information with contextual cues.

6. Conclusion

In this study, we investigated the intensity conditions for combining stimuli to present a dribbling sensation with SOVS, using simple waveforms with varying input amplitudes to identify the crucial cues for inducing the pseudo-dribbling phenomenon. The results from experiment 1 showed that the combination of different input amplitudes has a higher occurrence rate of the pseudo-dribbling phenomenon. Experiment 2 showed that the input amplitude affected the reality perceived by participants. When the stimulus is presented to the hand, the perceived reality goes along with the strength of the input amplitude, whereas for the stimulus given to the feet, an input amplitude that is too strong tends to lower the perceived reality. These results suggest that the combination of two different input amplitudes and the reality perceived by the user induces the pseudo-dribbling phenomenon. The obtained findings are expected to contribute to the development of simple haptic interfaces that incorporate hands and feet, providing insight into the spatiotemporal perception mechanism involving context.

Acknowledgements

This work was supported by JST SPRING, Grant Number JPMJSP2112, JST Moonshot R&D Program under Grant JPMJMS2013, Inamori Research Institute for Science, and partly based on a joint research project between Nagoya Institute of Technology and Nippon Telegraph and Telephone Corporation.

References

Achibet, M., Girard, A., Talvas, A., Marchal, M. and Lécuyer, A. (2015). Elastic-arm: human-scale passive haptic feedback for augmenting interaction and perception in virtual environments, in: *2015 IEEE Virtual Reality (VR), Arles, France*, pp. 63–68. DOI:10.1109/VR.2015.7223325.

Bensmaïa, S., Hollins, M. and Yau, J. (2005). Vibrotactile intensity and frequency information in the Pacinian system: a psychophysical model, *Percept. Psychophys.* **67**, 828–841. DOI:10.3758/BF03193536.

Bochereau, S., Terekhov, A. and Hayward, V. (2014). Amplitude and duration interdependence in the perceived intensity of complex tactile signals, in: *Haptics: Neuroscience, Devices, Modeling, and Applications (EuroHaptics 2014), Versailles, France*, pp. 93–100. DOI:10.1007/978-3-662-44193-0_13.

Cao, Y., Wang, Y., Dunn, H. A., Orlandi, C., Schultz, N., Kamasawa, N., Fitzpatrick, D., Li, W., Zeitz, C., Hauswirth, W. and Martemyanov, K. A. (2020). Interplay between cell-adhesion molecules governs synaptic wiring of cone photoreceptors, *Proc. Natl. Acad. Sci. USA* **117**, 23914–23924. DOI:10.1073/pnas.2004233117.

Coren, S. (1992). *The Left-Hander Syndrome: The Causes and Consequences of Left-Handedness*. The Free Press, New York, NY.

Galambos, P. (2012). Vibrotactile feedback for haptics and telemanipulation: survey, concept, and experiment, *Acta Polytech. Hung.* **9**, 41–65.

Geldard, F. A. and Sherrick, C. E. (1972). The cutaneous “rabbit”: a perceptual illusion, *Science* **178**, 178–179. DOI:10.1126/science.178.4057.178.

Hachisu, T. and Suzuki, K. (2018). Tactile apparent motion through human–human physical touch, in: *Haptics: Science, Technology, and Applications (EuroHaptics 2018), Pisa, Italy*, pp. 163–174. Springer, Cham. DOI:10.1007/978-3-319-93445-7_15.

Hachisu, T., Cirio, G., Marchal, M., Lécuyer, A. and Kajimoto, H. (2011). Virtual chromatic percussions simulated by pseudo-haptic and vibrotactile feedback, in: *ACE’11: Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology, Lisbon, Portugal*, Abstract 20. DOI:10.1145/2071423.2071448.

Hayward, V. and MacLean, K. E. (2007). Do it yourself haptics: Part I, *IEEE Robot. Automat. Mag.* **14**, 88–104. DOI:10.1109/MRA.2007.907921.

Hwang, I., Seo, J., Kim, M. and Choi, S. (2013). Vibrotactile perceived intensity for mobile devices as a function of direction, amplitude, and frequency, *IEEE Trans. Haptics* **6**, 352–362. DOI:10.1109/TOH.2013.2.

Jeon, W., Li, Y., Bahn, S. and Nam, C. S. (2013). Assessing the effectiveness of vibrotactile feedback on a 2d navigation task, in: *Human–Computer Interaction. Interaction Modalities and Techniques (HCI 2013), Las Vegas, NV, USA*, pp. 594–600. DOI:10.1007/978-3-642-39330-3_64.

Kato, H., Hashimoto, Y. and Kajimoto, H. (2010). Basic properties of phantom sensation for practical haptic applications, in: *Haptics: Generating and Perceiving Tangible Sensations (EuroHaptics 2010), Amsterdam, The Netherlands*, pp. 271–278. DOI:10.1007/978-3-642-14064-8_39.

Kim, J.-I., Jo, G., Koo, J.-H., Kim, D.-J., Kim, Y.-M. and Yang, T.-H. (2022). Development of a thin vibrotactile actuator based on the electrostatic force mechanism for large haptic touch interfaces, *Mobile Inform. Syst.*, 8331923. DOI:10.1155/2022/8331923.

Kim, S.-C., Kyung, K.-U. and Kwon, D.-S. (2007). The effect of sound on haptic perception, in: *Proceedings of the Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC 2007), Piscataway, NJ, USA*, pp. 354–360. DOI:10.1109/WHC.2007.110.

Kuhara, T., Komazaki, K., Watanabe, J. and Tanaka, Y. (2023). Spatiotemporal perceptions by single overlapped vibrotactile stimulation to multiple body locations, in: *2023 IEEE World Haptics Conference (WHC), Delft, The Netherlands*, pp. 1–6. DOI:10.1109/WHC56319.2023.10220614.

Lecuyer, A., Coquillart, S., Kheddar, A., Richard, P. and Coiffet, P. (2000). Pseudo-haptic feedback: Can isometric input devices simulate force feedback? in: *Proceedings of the IEEE Virtual Reality 2000 Conference, New Brunswick, NJ, USA*, pp. 83–90. DOI:10.1109/VR.2000.840508.

Minamizawa, K., Kakehi, Y., Nakatani, M., Mihara, S. and Tachi, S. (2012). Techtile toolkit: A prototyping tool for design and education of haptic media, in: *2012 IEEE Haptics Symposium (HAPTICS), Vancouver, BC, Canada*, pp. 353–356. DOI:10.1109/HAPTICS.2012.6183818.

Mott, M., Tang, J., Kane, S. K., Cutrell, E. and Moros, M. R. (2020). "I just went into it assuming that I wouldn't be able to have the full experience": Understanding the accessibility of virtual reality for people with limited mobility, in: *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility, Virtual Event, Greece*, Article 43. DOI:10.1145/3373625.3416998.

Nierhaus, T., Wesolek, S., Pach, D., Witt, C. M., Blankenburg, F. and Schmidt, T. T. (2023). Content representation of tactile mental imagery in primary somatosensory cortex, *eNeuro* **10**, ENEURO.0408–22.2023. DOI:10.1523/ENEURO.0408-22.2023.

O'Malley, M. K., Gupta, A., Gen, M. and Li, Y. (2006). Shared control in haptic systems for performance enhancement and training, *J. Dyn. Syst. Meas. Control* **128**, 75–85. DOI:10.1115/1.2168160.

Paljic, A., Burkhardt, J.-M. and Coquillart, S. (2004). Evaluation of pseudo-haptic feedback for simulating torque: A comparison between isometric and elastic input devices, in: *Proceedings of the 12th International Conference on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, IL, USA*, pp. 216–223. DOI:10.1109/HAPTICS.2004.1287185.

Robles-De-La-Torre, G. and Hayward, V. (2001). Force can overcome object geometry in the perception of shape through active touch, *Nature* **412**, 445–448. DOI:10.1038/35086588.

Sakuragi, R., Ikeno, S., Okazaki, R. and Kajimoto, H. (2015). Collarbeat: Whole body vibrotactile presentation *via* the collarbone to enrich music listening experience, in: *Proceedings of the 25th International Conference on Artificial Reality and Telexistence and 20th Eurographics Symposium on Virtual Environments, Tokyo, Japan*, pp. 55–62. DOI:10.1145/2820939.2820954.

Sallnäs, E.-L. (2010). Haptic feedback increases perceived social presence, in: *Proceedings of the 2010 International Conference on Haptics — Generating and Perceiving Tangible Sensations, Part II, Amsterdam, The Netherlands*, pp. 434–439. DOI:10.1007/978-3-642-14075-4_26.

Shirota, K., Uju, M., Peiris, R. and Minamizawa, K. (2019). Liquid-vr: Wetness sensations for immersive virtual reality experiences, in: *Haptic Interaction. AsiaHaptics 2018, Songdo, Korea*, pp. 485–491. DOI:10.1007/978-981-13-3194-7_57.

Wee, C., Yap, K. M. and Lim, W. N. (2021). Haptic interfaces for virtual reality: Challenges and research directions, *IEEE Access* **9**, 112145–112162. DOI:10.1109/ACCESS.2021.3103499.

Won, H.-I. and Altinsoy, M. E. (2020). Effect of auditory feedback on tactile intensity perception in a touchscreen application, *IEEE Trans. Haptics* **13**, 343–353. DOI:10.1109/TOH.2019.2947553.

Yamazaki, Y., Mitake, H. and Hasegawa, S. (2016). Tension-based wearable vibroacoustic device for music appreciation, in: *EuroHaptics 2016, London, United Kingdom*, pp. 53–62. DOI:10.1007/978-3-319-42321-06.

Yan, Y., Tan, R., Li, Y. and Huang, J. (2019). Wearables clock synchronization using skin electric potentials, *IEEE Trans. Mobile Comput.* **18**, 2984–2998. DOI:10.1109/TMC.2018.2884897.

Yao, K., Zhuang, Q. and Zhang, Q. (2024). A fully integrated breathable haptic textile, *Sci. Adv.* **10**, eadq9575. DOI:10.1126/sciadv.adq9575.