Presentation of Tracing Sensation through Combination of Disk Rotation and Vibration

Soma Kato[1], Yui Suga[1], Izumi Mizoguchi[1] and Hiroyuki Kajimoto[1]

[1] The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Japan
`{kato, suga, mizoguchi, kajimoto}@kaji-lab.jp`

Abstract. In our previous research, we introduced a technique for creating a natural tracing sensation. This was achieved by touching a rotating a small disk, the size of a fingertip. This approach is advantageous due to its compact design and the use of the physical sliding of objects. However, its limitation lies in its inability to represent multiple textures, limited to the surface material of the rotating disk. In contrast, numerous studies have explored varying textures through vibration. Consequently, we explored the potential of simulating diverse textures by merging this vibrational texture representation with the tracing sensation produced by the rotation of the disk. Based on this concept, we developed a system that provides stimulation through both disk rotation and vibration. Our system utilizes the same actuator for both rotating and vibrating the disk. We carried out an experiment to assess how realistic the generated stimulus feels, comparing it to the sensation of tracing an actual 1D grating plate. The findings indicated that we can realistically replicate multiple textures with varying degrees of roughness. Furthermore, our results showed that in many instances, the difference between the bump spacing and the vibration frequency had minimal impact on the perceived realism.

Keywords: Tracing Sensation, Rotating Disk, Vibrotactile, Texture.

1 Introduction

In virtual reality settings, conveying tactile sensations during object interactions, like grasping and manipulation, is crucial for augmenting the sense of immersion. On the other hand, the majority of VR controllers currently popular in VR applications primarily rely on vibration. This functionality is deemed inadequate for a broad spectrum of VR experiences.

In this study, we concentrate on tracing motions that are key in perceiving texture and friction of objects, as well as the tactile experience during such motions. Various techniques have been proposed to mimic the tracing sensation by replicating skin deformation during tracing. These methods generally fall into three categories: controlling the friction coefficient [1][2], moving the contact surface in a shear direction[3][4][5], and continuously rotating a disc or roller [6][7][8]. The last approach is especially noted for its high degree of realism, as it closely replicates the physical phenomenon during tracing and presents continuous shear stimuli. However, these methods often involve structures like a rotating drum to be touched against the finger. This tends to result in larger devices, necessary to make contact with the finger in a near-planar shape, which is difficult to use with multiple fingers and poses challenges in maintenance.

In a prior publication, we discussed a technique for creating a tracing sensation by having the fingertip contact the center of a rotating disk [9]. This approach drew inspiration from a study indicating that people may not discern or prioritize the precise direction of shear stimuli on the fingertip skin [10], and another study demonstrating that stimuli perpendicular to the tracing motion's direction can also heighten the sense of realism [6]. This method, contrasting with existing techniques like contacting the side of a rotating drum against the finger, allows for significant miniaturization by contacting the center of a rotating disk against the finger. In our previous report, we verified that this method can convey a realistic tracing sensation, and that the rotation's direction and speed have minimal impact on the perceived realism. However, our method is limited to presenting only one texture type, dependent on the disk's material, thus restricting its expressive range.

On the other hand, numerous studies have focused on presenting or altering perceived texture through the application of vibrations. Preechayasomboon et al. [11] found that vibrations ranging from 25-40 Hz could simulate textures with varying degrees of roughness. Choi et al. [12] captured and replayed the vibrations experienced when tracing surfaces of different roughness. Maeda et al. [13] utilized two types of actuators to create textures with distinct roughness. Asano et al. [14] observed that a 250 Hz vibration at the fingertip during tracing led to the perception of a smoother texture. Additionally, several studies have previously elucidated the relationship between vibration and friction from a physical perspective. Lu [15] demonstrated that the friction coefficient between vibrating objects is lower than that of non-vibrating objects, and that this reduction is proportional to the vibration frequency. Chowdhury et al. [16] demonstrated that the surface's friction coefficient diminishes as the vibration amplitude increases. As previously mentioned, there is a significant connection between texture perception and vibration.

In our study, we investigated a method to present the sensation of tracing an uneven surface. This was achieved by integrating vibration into our previously proposed technique of presenting a tracing sensation through a rotating disk. We utilized a motor that operates the disk's rotation for delivering vibration, with a single actuator handling both the rotation and the vibration. While tracing an uneven surface, vibrations are produced at the fingertip, with a frequency that correlates with the texture's fineness and the speed of tracing. Replicating these vibrations could enable the expression of various textures.

2 Implementation

2.1 Method of Presenting Tracing Sensation

We developed a device that replicates the tracing sensation by touching the center of a rotating disk to the fingertip (Fig. 1). This device comprises a disk, a 42:1 gear ratio DC motor for rotation, a magnetic encoder (1200ppr) for control, a load cell

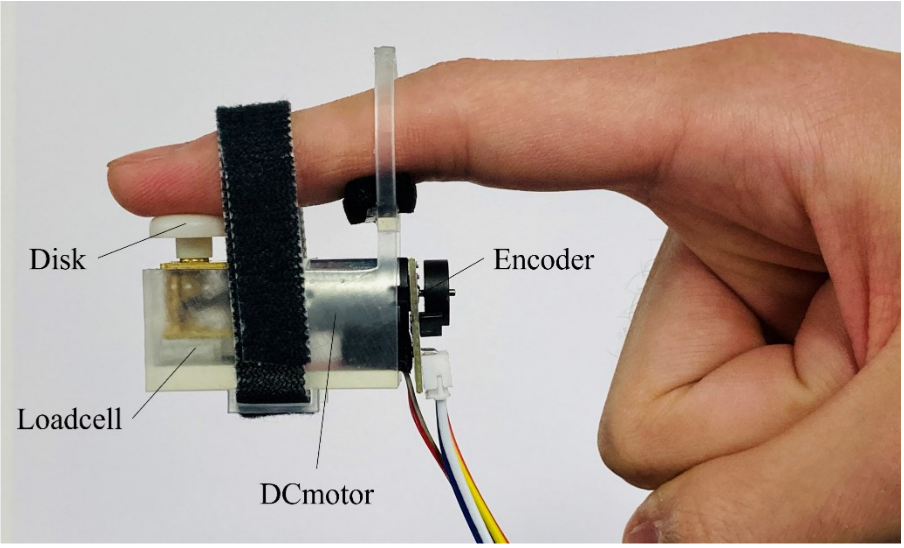

Fig. 1. Tracing Sensation Presentation Device. This device simulates the tracing sensation by rotating a disk that comes into contact with the fingertip.

(HSFPAR003A, Alps Alpine) to measure contact force, and velcro for securing the disk and finger. All components are securely held within a 3D printed framework. The frame and disk are constructed from 3D printer resin (Disk: Standard Resin White, Framework: Standard Resin Clear, Formlabs Form3). The disk, with a 12 mm diameter, matches the fingertip's contact area during tracing. We finished the disk's surface with #600 sandpaper for consistent texture. The device's total weight is 25.2 g.

The system's configuration is illustrated in Fig. 2. During tracing, a hand's movement is captured at 120 FPS by an optical motion capture system (OptiTrack Duo, Natural Point). The recorded hand positions are transmitted to a PC, processed in Unity at about 200 Hz, and then relayed to a microcontroller (XIAO RP2040, Seeed Studio). The disk's rotation speed is adjusted according to the hand's velocity. Previous studies indicate that reducing hand motion speed by up to 18% does not significantly affect perceived realism when correlating hand speed to disk circumference speed [9]. We applied this reduction to minimize the risk of rotational velocity causing control issues.

2.2 Presentation of Vibration

By introducing arbitrary waveforms into the DC motor that rotates the disk, we can simultaneously deliver vibration and shear forces at the output (end-effector). Numerous attempts have been made to utilize DC motors for conveying vibrations [17][18][19]. To analyze vibration details, we applied 100 Hz vibration from the device to an author's index finger, with a 9-axis accelerometer (BMX055, Bosch Sensortec) on the nail. The sensor captured the output, depicted in Fig. 3. The graph indicates a dominant x-axis vibration (orthogonal to the finger side) and minor z-axis vibration (orthogonal to the finger belly). This slight z-axis vibration likely results from motor

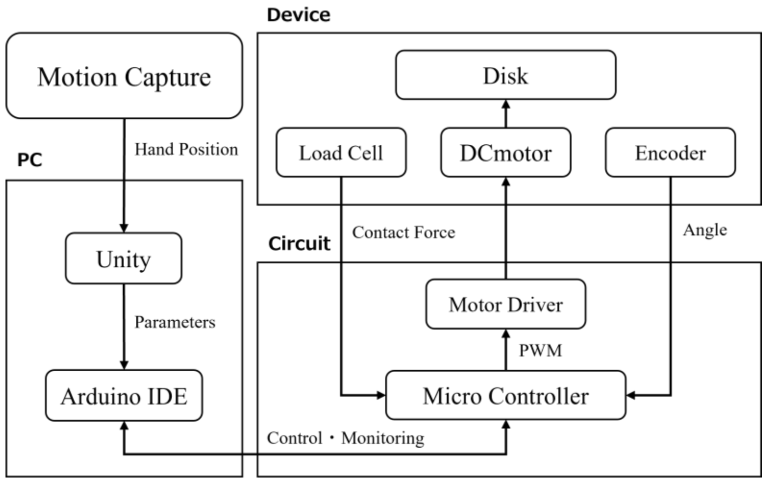

Fig. 2. Overall system configuration.

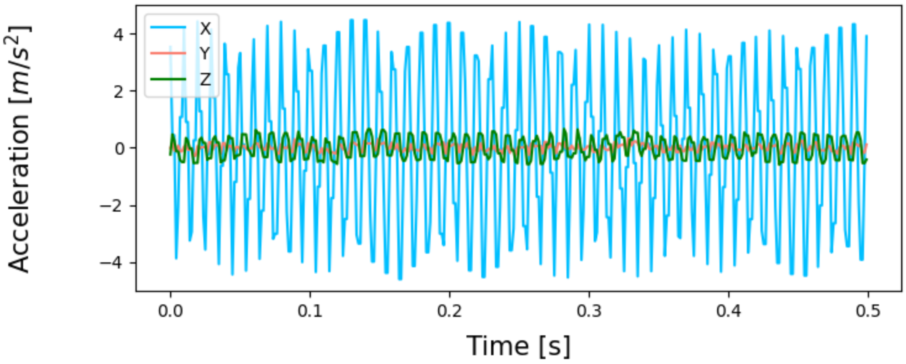

Fig. 3. Output waveform for a 100 Hz input: Here, the X-axis represents the direction perpendicular to the side of the finger, the Y-axis aligns parallel to the side of the finger, and the Z-axis is perpendicular to the finger belly.

vibration reaching the fingertip. Additionally, we examined acceleration amplitudes in the x-axis at 50 Hz, 100 Hz, and 200 Hz frequencies, applying Fast Fourier Transform (FFT) to the data. As shown in Fig. 4, vibrations up to 200Hz can be reliably produced to a certain extent.

This system employs PD control for disk rotation, and adding vibration waveforms to the control signal could impact the control. Hence, we monitored the encoder's output when subjected to vibrations of various frequencies. It was found that the encoder's low resolution meant vibrations had minimal effect on its readings. Nonetheless, to further minimize influence, we smoothed the encoder values by implementing a low-pass filter (IIR filter) and utilized these adjusted values for PD control.

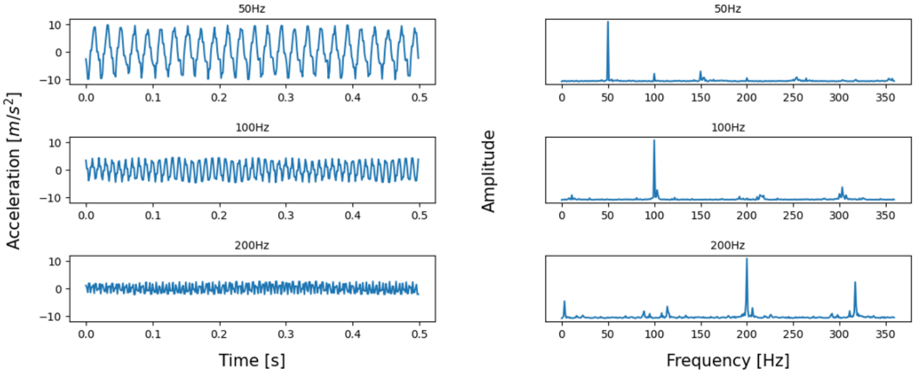

Fig. 4. Output waveforms (left) and the results of their discrete Fourier transform (right) for inputs of various frequencies.

3 Experiment

Experiments were conducted to assess the realism of the stimuli produced by the device, comparing it to the sensation of tracing over different actual 1D gratings plate.

3.1 Presentation Stimulus

In this experiment, we used 1D gratings depicted in Fig. 5, produced by a 3D printer using the same material as the device disks (Standard Resin Black, Formlabs Form3). We created three types of plates with varying bump spacings: 1.0 mm, 2.0 mm, and 4.0 mm (e.g., 1 mm entails 1.0 mm raised and 1.0 mm recessed sections). The groove depth on all plates was 1 mm. These plates are referred to as Smooth, Middle, and Rough, respectively. To ensure uniform surface conditions, all plates were finished with #600 sandpaper, similar to the disks. The vibration at the fingertip while tracing these plates correlates with the bump spacing and the tracing motion's velocity. To mimic this, we dynamically adjusted the vibration frequency based on the bump spacing and tracing speed. For instance, a plate with 1 mm spacing (2 mm per cycle) will generate a 100 Hz vibration at a tracing speed of 200 mm/s, and 25 Hz at 50 mm/s. Yet, due to instability in minor hand movements, vibrations below 10 Hz were not presented. Vibrations corresponding to each type of plate are also labeled as Smooth, Middle, and Rough. We used a square wave as the input waveform for the vibration to align with the plates' unevenness.

We utilized two conditions for stimuli presentation: vibration only (Vibration condition) and combined vibration and rotation (Vibration+Rotation condition). The decision to omit a rotation-only condition was made to prevent the relative overvaluation of the other conditions. Since the rotation-only condition couldn't replicate any texture unevenness, it was less realistic compared to the others, potentially leading to very low

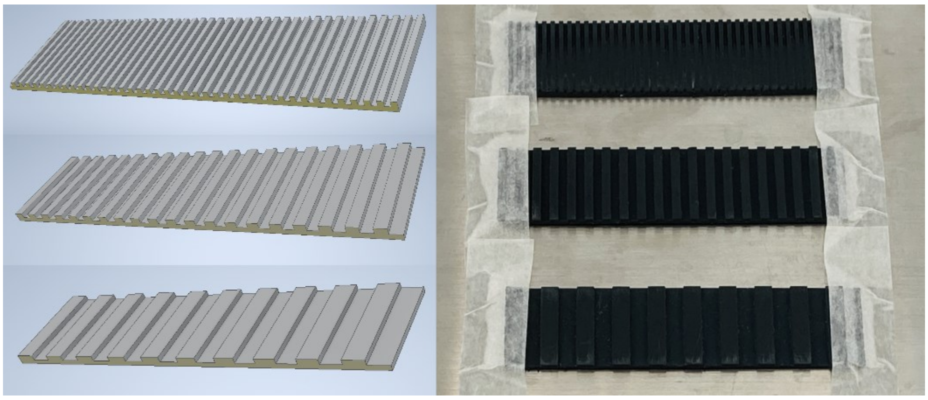

Fig. 5. CAD data of the 1D grating utilized in the experiment (left) and the 3D printed plate (right).

evaluations from subjects. Consequently, there were 18 experimental conditions: 3 real plate textures (Smooth, Middle, Rough) × 3 vibration patterns (Smooth, Middle, Rough) × 2 stimulus presentations (Vibration, Vibration+Rotation). In the experiment, each condition was randomly presented once to each participant.

3.2 Setup

Ten participants (ages 22-27, all males) were involved in this experiment. They wore fingerless gloves fitted with retroreflective material for tracking hand movements. To negate auditory distractions, participants also wore headphones playing white noise. The ethics committee of the author's university granted approval for this experiment.

3.3 Procedure

Participants initially traced one of the real plates, as instructed by the experimenter, with a pressure of approximately 50gf until they memorized its sensation. The device was then attached to the right index finger. During this, they adjusted the Velcro's tightness to align the load cell's output with 50g. Following this, participants, with their eyes closed, engaged in a simulated tracing task in the air and rated the realism of the stimuli on a seven-point Likert scale (1: not at all realistic - 7: as realistic as the actual plate). This process was repeated 18 times, covering each condition. Lastly, participants were invited to provide open-ended feedback. Fig. 6 depicts the experimental setup.

3.4 Results

The experimental results are depicted in Fig. 7. For clarity, texture conditions are represented as plate-vibration stimuli, abbreviated by their initial letters. For example, 'M-

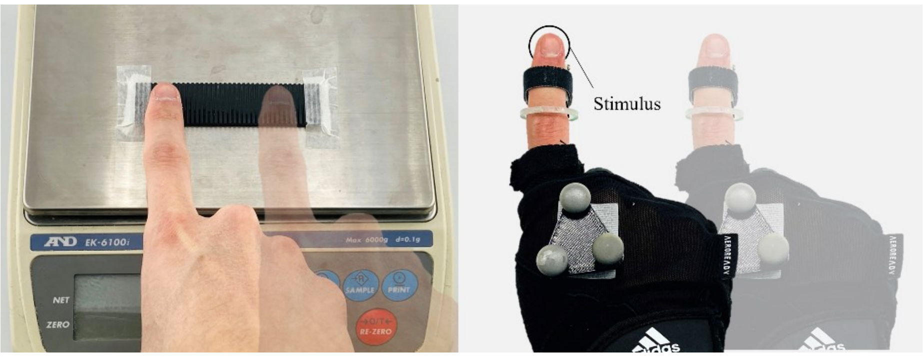

Fig. 6. Experimental Scene. Participants initially traced the 1D grating plate (right) to feel its texture, then donned the device and assessed the presented stimuli (left).

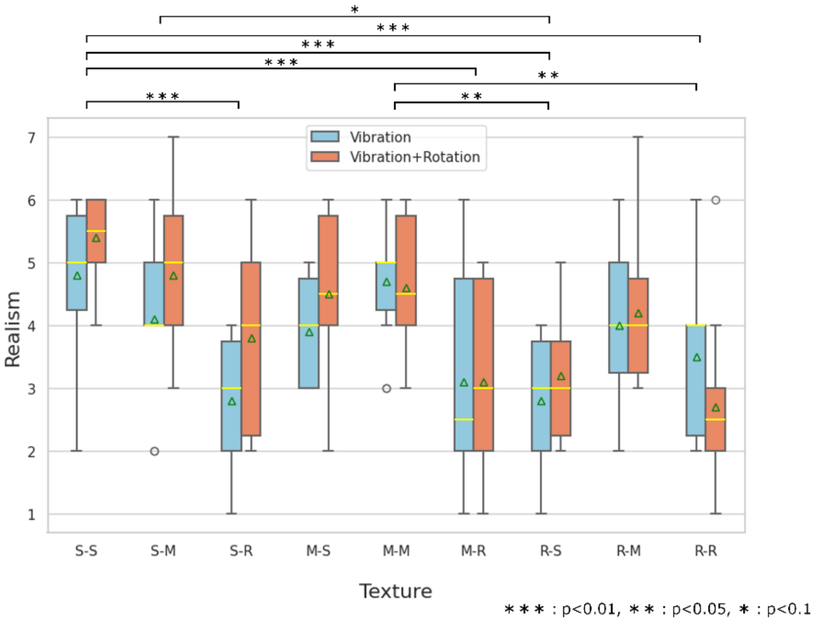

Fig. 7. Results of Experiment. Dots indicate outliers and triangles indicate averages.

S' denotes the condition where a Middle-textured plate was traced, followed by a vibration akin to a Smooth-textured plate. The aligned rank transformed analysis of variance [20] was applied to the data. The analysis revealed a significant main effect only in the texture factor. Subsequently, multiple comparisons using the Bonferroni method indicated significant differences between the S-S and S-R conditions ($p<0.01$), S-S and M-R conditions ($p<0.01$), S-S and R-S conditions ($p<0.01$), S-S and R-R conditions ($p<0.01$), S-M and R-S conditions ($p<0.1$), M-M and R-S conditions ($p<0.05$), and between M-M and R-R conditions ($p<0.05$). No interaction effects were found.

3.5 Discussion

The analysis of experimental data revealed that for each texture, there was at least one condition that was rated with a realism level of 4 or higher out of 7, indicating that our proposed method can effectively replicate each texture to some extent degree of realism. Moreover, the results confirmed that the combination of plate and vibration impacts the perceived realism. On the other hand, it was also observed that the most realistic outcomes were not always achieved with matching plate-vibration combinations. The only significant difference within the same plate conditions was observed between the S-S and S-R conditions. This implies that precisely replicating the vibration frequency may not be crucial.

Relative to the Smooth and Middle-textured plates, conditions involving the Rough-textured plate appeared less realistic. Generally, a wider bump interval leads to greater vibration amplitude during tracing. The Rough-textured plate, with its 4 mm spacing, likely produced substantial vibrations at the fingertips. In this regard, the vibration intensity provided by our device may have been insufficient, leading to a decreased sense of realism. Moreover, our system excluded vibrations below 10 Hz to stabilize device operation, which may have substantially impacted tracing on the Rough-textured plate. In fact, many participants noted a mismatch between the sensation of tracing the Rough-textured plate and the stimuli delivered by the device. This implies that the device's vibration intensity range might be adequate only for representing roughness up to the level of a Middle-textured plate.

In this experiment, no significant differences were observed between the Vibration condition and Vibration+Rotation condition. This indicates that for the 1D gratings used in our study, a reasonably realistic tracing experience could be achieved with vibration only. On the other hand, considering the median values, the Vibration+Rotation condition may be more suitable than Vibration condition when the real object is Smooth. On the contrary, this trend is not evident when the real object is Rough. In essence, realism could be enhanced when the object is smooth.

It's important to recognize that the vibration used in this study differs from that of a typical vibrator, as it has a substantial shear component relative to the finger belly. While future comparisons with standard vibrators are necessary, it's noteworthy that the shear vibration from the rotating disk, generated by the same motor for rotation successfully replicated the texture of 1D gratings realistically.

This study currently has several limitations. Firstly, the textures employed were all similar square-wave gratings with only the difference of wavelength. Research suggests that tracing speed has minimal impact on texture perception [21], indicating that it's not the vibration frequency per se, but the frequency component distribution that matters in texture perception. On the other hand, as all real objects used in our experiment had the same square-wave shape and the vibrations presented were also square waves, it's possible that all textures were perceived as somewhat uniform. To address this, a variety of texture types should be considered in future research.

The second limitation of our study is the lack of results for materials with varying friction coefficients. The similarity in results between the Vibration condition and Vibration+Rotation condition may be attributed to the lateral displacement force of the skin, or in other words, the coefficient of friction, not being a significant factor in material differentiation (the coefficient of friction was generally low). On the other hand, how the same disk could represent different tactile sensations for materials with distinct friction coefficients remains unclear. It might be essential to explore the application of existing surface friction modulation methods [1][2] to the disk itself.

4 Conclusion

In our study, we explored a method for simulating the sensation of tracing various textured surfaces through a combination of shear stimulation via disk rotation and vibration stimulation. We developed a device capable of independently delivering each stimulus using the same actuator. This device employs a DC motor as its actuator and can provide vibration at arbitrary frequency up to approximately 200 Hz, in addition to rotational stimulation.

We carried out an experiment to assess the realism of stimuli produced by our device, based on the sensation of tracing an actual 1D grating plate. We utilized two types of stimuli: vibration only, and a combination of vibration and rotation. Three distinct types of plates were employed, each featuring different bump spacings, and three corresponding types of vibration stimuli were utilized to simulate each plate. The overall results indicated that the presence or absence of rotation and the congruence between plate texture and vibration frequency did not significantly impact the perceived realism. On the other hand, smooth textures tended to enhance realism when paired with rotation, and the realism decreased with the presentation of highly inconsistent vibrations.

Looking ahead, our goal is to validate the efficacy of this method across a broader range of textures, apply to multiple fingers, and explore other texture presentation techniques beyond vibration, such as modulation of surface friction.

References

1. O. Bau, I. Poupyrev, A. Israr, and C. Harrison, “TeslaTouch: electrovibration for touch surfaces,” in Proceedings of the 23nd annual ACM symposium on User interface software and technology, in UIST ’10. New York, NY, USA: Association for Computing Machinery, Oct. 2010, pp. 283–292.
2. M. Wiertlewski, R. Fenton Friesen, and J. E. Colgate, “Partial squeeze film levitation modulates fingertip friction,” Proceedings of the National Academy of Sciences, vol. 113, no. 33, pp. 9210–9215, Aug. 2016.
3. V. Yem, R. Okazaki, and H. Kajimoto, “FinGAR: combination of electrical and mechanical stimulation for high-fidelity tactile presentation,” in ACM SIGGRAPH 2016 Emerging Technologies, in SIGGRAPH ’16. New York, NY, USA: Association for Computing Machinery, Jul. 2016, pp. 1–2.
4. S. B. Schorr and A. M. Okamura, “Three-Dimensional Skin Deformation as Force Substitution: Wearable Device Design and Performance During Haptic Exploration of Virtual Environments,” IEEE Transactions on Haptics, vol. 10, no. 3, pp. 418–430, Jul. 2017.

5. P. Zhang, M. Kamezaki, Y. Hattori, and S. Sugano, “A Wearable Fingertip Cutaneous Haptic Device with Continuous Omnidirectional Motion Feedback,” in 2022 International Conference on Robotics and Automation (ICRA), May 2022, pp. 8869–8875.
6. E. Whitmire, H. Benko, C. Holz, E. Ofek, and M. Sinclair, “Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller,” in Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, in CHI ’18. New York, NY, USA: Association for Computing Machinery, Apr. 2018, pp. 1–12.
7. M. J. Kim, N. Ryu, W. Chang, M. Pahud, M. Sinclair, and A. Bianchi, “SpinOcchio: Understanding Haptic-Visual Congruency of Skin-Slip in VR with a Dynamic Grip Controller,” in Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems, in CHI ’22. New York, NY, USA: Association for Computing Machinery, Apr. 2022, pp. 1–14.
8. U. Martinez-Hernandez and G. A. Al, “Wearable fingertip with touch, sliding and vibration feedback for immersive virtual reality,” in 2022 IEEE International Conference on Systems, Man, and Cybernetics (SMC), Oct. 2022, pp. 293–298.
9. S. Kato, Y. Suga, I. Mizoguchi and H. Kajimoto, " Presentation of a Tracing Sensation by Means of Rotation Stimuli," Proc. of IEEE HapticsSymposium 2024, Long Beach April 7-10th, 2024 (accepted).
10. V. Yem, M. Shibahara, K. Sato, and H. Kajimoto, “Expression of 2DOF Fingertip Traction with 1DOF Lateral Skin Stretch,” in Haptic Interaction, S. Hasegawa, M. Konyo, K.-U. Kyung, T. Nojima, and H. Kajimoto, Eds., in Lecture Notes in Electrical Engineering. Singapore: Springer, 2018, pp. 21–25.
11. P. Preechayasomboon, A. Israr, and M. Samad, “Chasm: A Screw Based Expressive Compact Haptic Actuator,” in Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, in CHI ’20. New York, NY, USA: Association for Computing Machinery, Apr. 2020, pp. 1–13.
12. I. Choi, E. Ofek, H. Benko, M. Sinclair, and C. Holz, “CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality,” presented at the CHI 2018, Apr. 2018.
13. T. Maeda, S. Yoshida, T. Murakami, K. Matsuda, T. Tanikawa, and H. Sakai, “Fingeret: A Wearable Fingerpad-Free Haptic Device for Mixed Reality,” in Proceedings of the 2022 ACM Symposium on Spatial User Interaction, in SUI ’22. New York, NY, USA: Association for Computing Machinery, Dec. 2022, pp. 1–10.
14. S. Asano, S. Okamoto, and Y. Yamada, “Vibrotactile Stimulation to Increase and Decrease Texture Roughness,” IEEE Transactions on Human-Machine Systems, vol. 45, no. 3, pp. 393–398, Jun. 2015.
15. J. Lu, “The Effect of Mechanical Vibration on Interfacial Friction,” IOP Conf. Ser.: Mater. Sci. Eng., vol. 490, no. 5, p. 052020, Apr. 2019.
16. M. A. Chowdhury and M. Helali, “The effect of amplitude of vibration on the coefficient of friction for different materials,” Tribology International, vol. 41, no. 4, pp. 307–314, Apr. 2008.
17. V. Yem, R. Okazaki and H. Kajimoto, "Vibrotactile and Pseudo Force Presentation using Motor Rotational Acceleration." Proc. of IEEE HapticsSymposium 2016, Philadelphia April 8-11th, pp. 47-51, 2016.
18. R. Gourishetti and K. J. Kuchenbecker, “Evaluation of Vibrotactile Output From a Rotating Motor Actuator,” IEEE Transactions on Haptics, vol. 15, no. 1, pp. 39–44, Jan. 2022.
19. M. Manabe, K. Ushiyama, A. Takahashi, and H. Kajimoto, “Vibrotactile Presentation using a Motor within a Housing and Rotor Fixed to the Skin,” in 2021 IEEE World Haptics Conference (WHC), Jul. 2021, pp. 906–911.

20. J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins, “The aligned rank transform for nonparametric factorial analyses using only anova procedures,” in Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, in CHI ’11. New York, NY, USA: Association for Computing Machinery, May 2011, pp. 143–146.
21. Z. M. Boundy-Singer, H. P. Saal, and S. J. Bensmaia, “Speed invariance of tactile texture perception,” Journal of Neurophysiology, vol. 118, no. 4, pp. 2371–2377, Oct. 2017.