Rotational Skin-stretch Distribution Creates Directional Force Sensation on the Wrist

Rodan Umehara[1 [0009-0003-5180-1553]], Arata Horie[1,2 [0000-0002-8161-5036]], and Kouta Minamizawa[1 [0000-0002-6303-5791]]

[1] Keio University Graduate School of Media Design, Yokohama, Japan
`{umeharar.ab,a.horie,kouta}@kmd.keio.ac.jp`
[2] commissure, inc., Tokyo, Japan

Abstract. This study aims to develop a compact, palm-free wearable system for mixed-reality(MR) environments that does not interfere with interactions with real objects. We propose a novel wearable system that presents the direction of force through a rotational skin-stretch distribution to the wrist by utilizing four independently controlled rotating tactors. Two control rules, local and global, are proposed to dictate the stimulus distribution. The local stimulus distribution produces a local distortion distribution by combining the rotation of two specific tactors and suggests a direction. The global control rule aims to present the overall direction of the force by combining the directional forces presented on both the palm and back of the hand. The capability of the system to present the perceptual intensity and directional stimuli was confirmed through two experiments. The first experiment confirmed that the proposed system could present perceived intensity. The second experiment showed that the global control law could present stimuli in the front-back direction, whereas the local control law could present stimuli in other directions except for upwards. These findings suggest that proposed system has potential to enhance MR experience by simulating static force sensations, such as the weight of virtual objects.

Keywords: Skin Stretch · Mixed Reality · Palm Free.

1 Introduction

In mixed/augmented Reality (MR/AR) environments, haptic feedback should be presented in a palm-free manner to avoid interference during interactions with real objects. Although haptic presentation devices for virtual reality (VR) that completely cover the hands, such as gloves[11], are acceptable in MR/AR, design guidelines require that they do not hinder hand interactions with real objects. To realize expectations in MR/AR environments that include haptic feedback, researchers have proposed methods for presenting stimuli to parts of the body other than the original sites of perception.

Several methods have been proposed for providing haptic feedback by applying force to the fingertip using devices mounted on different parts of the body. Kameoka et al. [8] proposed a suction tactile display device that realizes a hands-free haptic experience by transferring pressure sensations felt at the fingertips to the face. This device can present the hardness and softness of virtual objects felt at the fingertips by dynamically controlling the suction pressure according to the user's movements, but it has the problem that the degree of freedom of presenting force is low. Pezent et al. [12] proposed a system that presents the reaction force and texture of virtual objects by squeezing and applying vibrotactile stimuli to the wrist. Although this device is compact and excels in squeezing efficiency, it faces the challenge of having limited degrees of freedom in the force it can present. Moriyama et al. [9] proposed a method that uses a five-link mechanism to present two degrees of freedom of the force applied to the fingertips of the forearm. This study demonstrated significant improvement in fingertip task performance using this device. However, further increasing the degrees of freedom of the force would require a new approach because of the resulting increase in the size and complexity of the structure.

In contrast, another method has been proposed to miniaturize the structure of devices using rotational skin stretching. Chinello et al. [2] proposed a forearm-mounted device that presents rotational and translational forces through four cylindrical end effectors rotating around a horizontal axis against the skin. This system is a viable solution for human guidance and remote robot operation systems for navigation feedback. Conversely, Horie et al. [7] proposed a forearm-mounted system integrating force myography and skin stretch, demonstrating a consistent model between the rotation angle of tactors around an axis perpendicular to the skin and the perceived intensity. There have been reports on the perception of rotational direction using a rotational skin stretch [1] and on the perception of the direction of stimulus movement through moving phantom sensation using its spatiotemporal distribution [6]. However, the distribution of rotational skin-stretch stimuli for presenting forces along multiple axes in a directionally remains unclear. If the distribution of the rotational skin-stretch stimuli can facilitate the presentation of static and translational forces, it could allow the presentation of contact with virtual objects, a sense of weight, and self-motion sensations through compact wearable systems.

In this paper, we evaluate the perceived intensity and direction of force when a rotational skin stretch, generated by rotation around an axis perpendicular to the skin, is presented to the wrist for the presentation of translational forces. An experimental device was created to investigate the type of skin deformation distribution perceived as a force. As part of the system evaluation, we demonstrated that each location for presenting a rotational skin-stretch could present the desired stimulus intensity. Furthermore, we conducted basic user experiments to verify whether this system is applicable to directional haptic feedback. Finally, experimental results and future developments are discussed.

2 Proposed Method

2.1 Hardware and Control

The proposed hardware shown in Fig. 1 is a wristband-type wearable device. It employs four circular tactors that transmit stimuli through rotation. Each tactor was mounted on the palm and shell of the wrist. Each tactor had a diameter of 25 mm and a thickness of 3 mm, utilizing a self-adhesive gel to minimize slippage and maximize the skin contact area with a penetration index of 55(JIS K2207). Four small serial servomotors

(RSV10–1003ESG400, Orbray) were employed and a slim form factor was obtained. The housing, 3D printed using a TPU(Shore-A95) material, allows the housing to flex, keeping the tactors as perpendicular to the skin as possible. The maximum distance between the tactors was 50 mm. Control is managed via a PC application and a microcontroller (M5 Atom)-equipped board, with angle instructions determined in Unity(Unity 3D) and command generation and serial communication handled by TouchDesigner (Derivative). The board features a buffer circuit for half-duplex communication and supplies power operating at a control cycle of 120Hz.

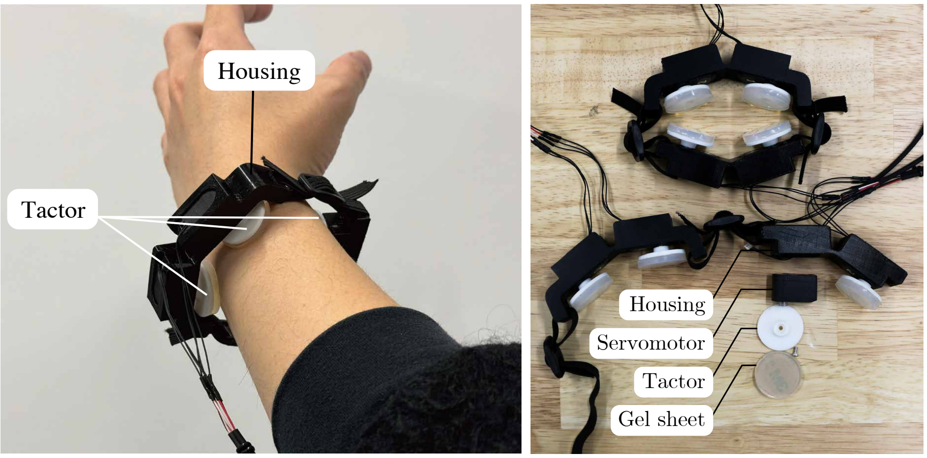


Fig. 1. Wearable rotational skin-stretch distribution device. The housings are connected with rubber bands.

2.2 Control Strategy

The device features four actuators that can be controlled independently to generate a strain distribution on the wrist by adjusting the rotation direction and angle. This capability allows for complex stimulus design, including creating translational strain between the tactors on the palm and back of the hand or presenting localized stimuli by activating specific tactors. This flexibility facilitated a wide range of tactile sensations.

As examples of stimulations that can be designed, we propose two control rules for the proposed device to present directional forces through a rotational skin-stretch distribution: local and global control rules, as shown in Fig. 2. The local control rule is expected to present a direction by creating a localized distribution of strain through a combination of specific tactor rotations. The direction of rotation of each tactor was designed such that the skin was distorted in the designated direction between the two adjacent rotating tactors. By activating only the tactors in the intended direction, this approach is likely to make users perceive the force in a specific direction. Because device does not arrange tactors in a front-back configuration, the local rule is expected to induce forces in the up-down and inside-outside directions. The global control rule aims to present the overall direction of the force by combining the directional forces presented on both the palm and back of the hand. This control law rotates all four tactors and produces skin distortion in a designated direction by combining the rotations of the two adjacent tactors on the palm and shell sides of the wrist. For example, presenting the inside direction using the global rule involves creating opposite strains on the palm and back of the hand, in addition to local stimulus presentation. The global rule also proposes a design for presenting the front or back directions by creating strains in the same direction on both the palm and back sides.

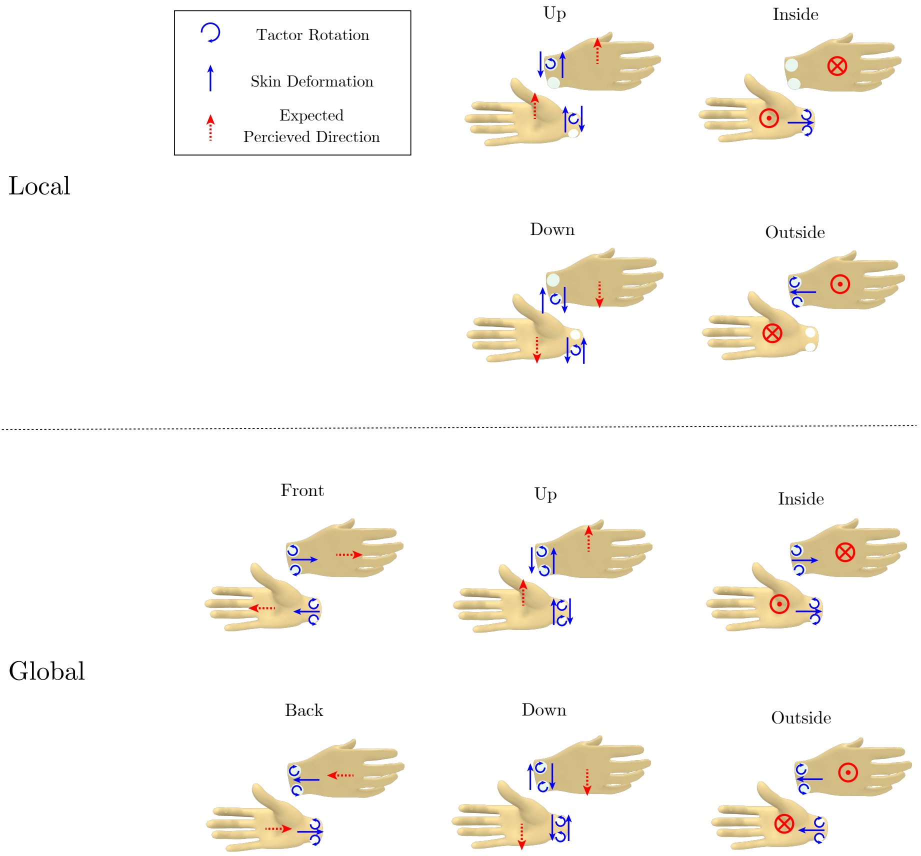


Fig. 2. Rotational Skin-Stretch Distribution

3 Evaluation

In this section, we describe the experiments related to the perceived intensity of rotational skin-stretch stimuli at various tactile presentation locations and the perception of force direction owing to the distribution of rotational skin-stretch stimuli. The experiments in Subsection 3.1 attempted to establish a relationship between the perceived intensity of the stimulus and the magnitude of the rotational skin stretch presented by the device using Stevens' law. This served as a preliminary validation that the device could be used to present stimuli with controllable intensity.

3.1 Experiment1: relationship between rotation angle and perceived intensity

The objective of this experiment was to identify the relationship between the rotation angle in the proposed system and perceived intensity. In addition, by evaluating the consistency of the models obtained through experiments, we aimed to confirm that the system met the required functionalities within a predetermined range.

Participants Eleven participants (mean age 25.7 years, range 22–33 years, 7 males and 4 females) participated in the experiment. Ten participants were right-handed, and one was left-handed.

Stimulus Tactile stimuli were presented by the rotation of a single servomotor mounted on a force feedback device. The rotation angle is controlled according to the five profiles shown in Fig. 3. The maximum angle varied between 10° and 50°, and both clockwise and counterclockwise rotations were possible. All presentation durations were identical for all stimuli. Each trial included a reference stimulus, and the rotation angle of the reference stimulus was 30°.

Procedure The experimental setup is illustrated in Fig. 4. The participants were informed that a test stimulus would be presented after the reference stimulus. Participants were then asked to rate the intensity of the test stimulus relative to that of the reference stimulus using a magnitude estimation method. The intensity of the reference stimulus was assumed to be 30, and the participants provided their numerical ratings orally. Each participant repeated each test stimulus three times for 30 trials for each location. During the experiment, participants were asked to listen to white noise through noise-cancelling headphones. The order of the trials at each location was randomized, with a rest period of at least 30 s between each of the 30 trials. Eight stimulus presentation locations were selected on both wrists for 240 trials. The total duration of the experiment was approximately 80 min, including the rest period.

Results Fig. 5 shows the perceived intensity according to the rotation angle for each stimulus location. Stimuli with a 10° rotation angle were excluded because of their extremely low perceived intensity, making it difficult for the subjects to assess their strength numerically. A consistent trend was observed, regardless of the hand side or

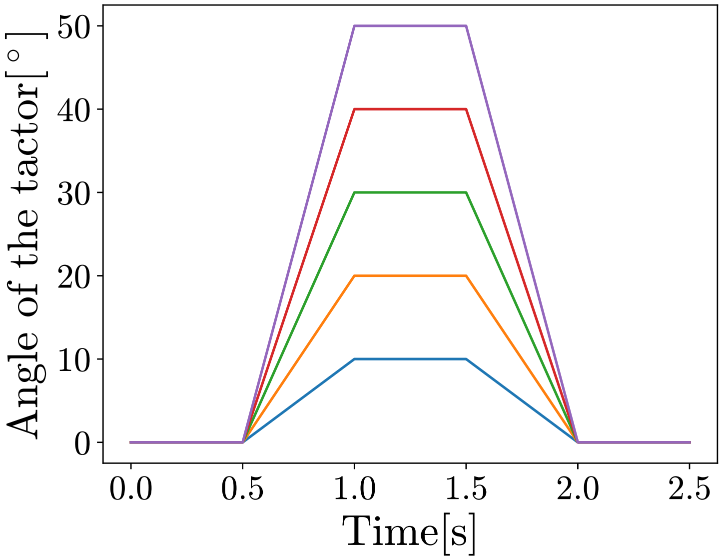


Fig. 3. Rotation angle profiles in experiment 1

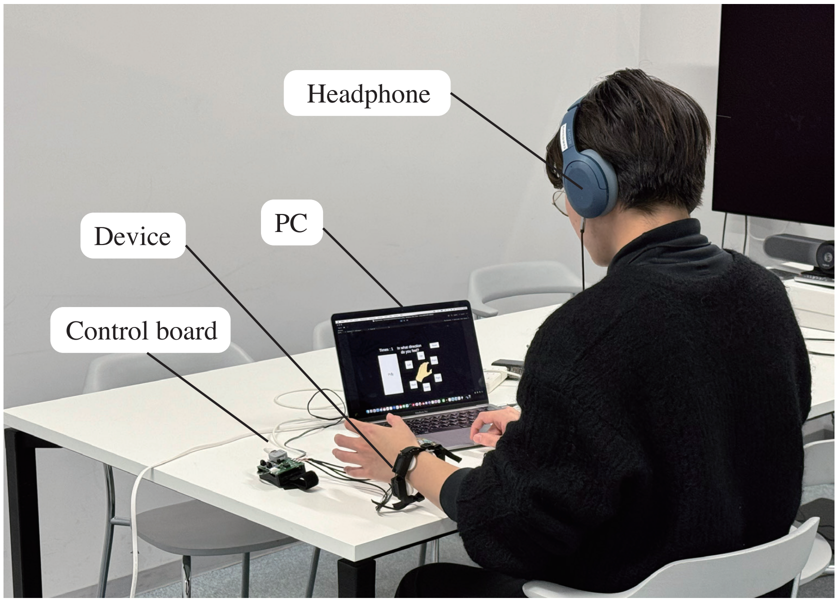


Fig. 4. Experimental environment

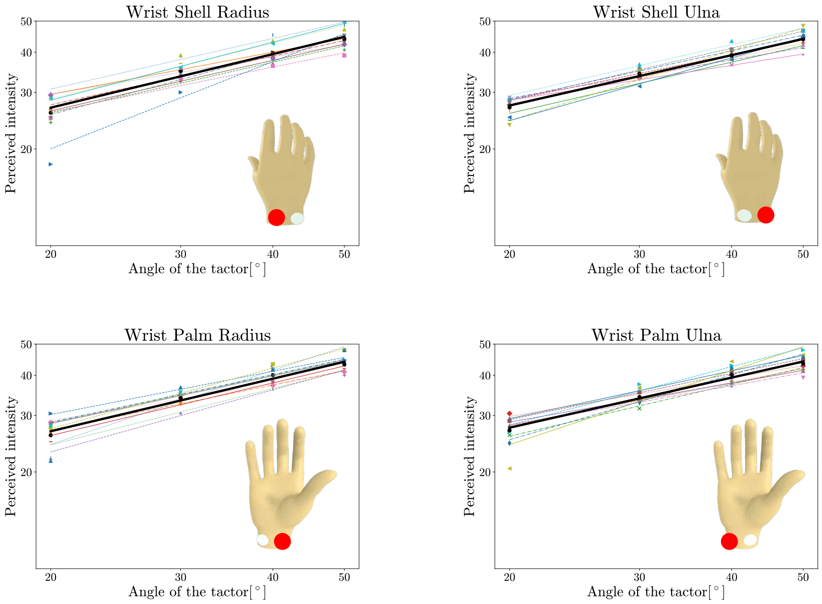


Fig. 5. Perceived intensity when the rotation angle is greater than 20° for each location. Red circles shown on the wrists indicate the location of the stimulation. Stimuli with a 10° rotation angle were excluded due to their extremely low perceived intensity, making it difficult for subjects to numerically assess their strength. The data were combined because a consistent trend was observed regardless of the hand side and direction of rotation. The dashed lines in the figure represent models fitted to individual participant data according to Stevens' law, while the solid black lines represent models fitted to the average of all participants' data. Plotted in both logarithmic plots.

rotation direction, allowing data integration. The colored points represent the average responses of the participants under each condition, whereas the black circles indicate the average responses across participants for that condition.

Stevens' law is an established method for modeling the relationship between physical and perceived intensities:

$$\psi = k\phi^{\alpha} \tag{1}$$

where ψ is the perceived intensity, ϕ is the physical quantity of the stimulus, α is the intrinsic power exponent for the perceptual modality, and k is a constant of scale. Fitting equation 1 to the average of the responses to each direction of rotation for each tactor across participants, except for stimuli with a rotational angle magnitude of 10°, yields the following.

$$\psi_{WristShellRadius} = 5.118\phi^{0.554}(R^2 = 0.984) \tag{2}$$

$$\psi_{WristShellUlna} = 5.747\phi^{0.520}(R^2 = 0.997) \tag{3}$$

$$\psi_{WristPalmRadius} = 5.266\phi^{0.543}(R^2 = 0.984) \tag{4}$$

$$\psi_{WristPalmUlna} = 5.827\phi^{0.518}(R^2 = 0.990) \tag{5}$$

All the models exhibited a coefficient of determination exceeding 0.98, indicating that the perceived intensity of the stimuli could be explained by these models. The difference in exponents between the models for different presentation locations remained within 0.05, suggesting that the intensity of the rotational skin-stretch stimuli at the wrist was not significantly affected by the stimulus presentation location. he dashed lines in the figure represent models fitted to individual subject data according to equation 1, while equations 2–5 are represented by black solid lines.

This experiment revealed perceptual intensity models for rotational skin-stretch stimuli at each stimulus location, showing that the proposed device can present perceptual intensities in angle regions of 20° or more.

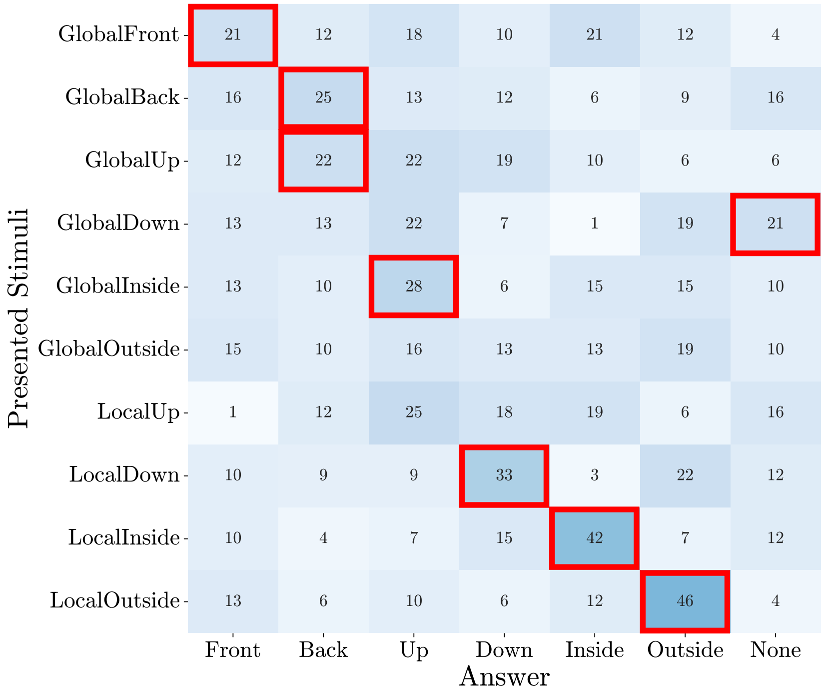
3.2 Experiment2: perceived direction of rotational skin-stretch distribution

The purpose of this experiment was to determine whether the forces due to the rotational skin-stretch stimulus distribution produced by the combination of tactor rotation directions could provide a directional presentation.

Participants The participants of experiment1 continued to participate in this experiment.

Stimulus Tactile stimuli were presented through the rotation of four servomotors equipped with a haptic feedback device. The rotational skin-stretch stimulus distribution followed the patterns of rotation directions proposed in Section 2.2. In each trial, the maximum rotation angle for each tactor was 30°, and the temporal profile was the same as that used in experiment 1, as shown in Fig. 3.

Procedure The experimental setup was the same as that used in experiment 1. The participants were informed that they would be presented with test stimulus distributions expected to indicate the following directions: forward, backward, up, down, inside, or outside. They were asked to identify the direction they felt was indicated by the test stimulus distribution, with an option to respond "None" if no direction was perceived. The participants indicated their directions using the UI displayed on the PC. Each participant performed 30 trials with random repetitions of 10 types of stimuli with one hand, took a 5-minute break, and then repeated the process with the other hand, totaling 60 trials. The entire experiment lasted approximately 40 min.



	Front	Back	Up	Down	Inside	Outside	None
GlobalFront	21	12	18	10	21	12	4
GlobalBack	16	25	13	12	6	9	16
GlobalUp	12	22	22	19	10	6	6
GlobalDown	13	13	22	7	1	19	21
GlobalInside	13	10	28	6	15	15	10
GlobalOutside	15	10	16	13	13	19	10
LocalUp	1	12	25	18	19	6	16
LocalDown	10	9	9	33	3	22	12
LocalInside	10	4	7	15	42	7	12
LocalOutside	13	6	10	6	12	46	4

Fig. 6. Confusion matrix showing response rates (%) for each skin-stretch distribution. Cells surrounded by red squares are those revealed to be significantly more frequent in the residual analysis ($p < 0.05$).

Results The chi-square test allowed us to determine whether there was a difference in the crosstabulation as a whole, and the residual analysis allowed us to determine which cells were biased. Therefore, a chi-square test was conducted on the experimental results, represented in Fig. 6, and a significant difference was obtained ($\chi^2 = 205.83$, $p < 0.0001$). Residual analysis indicated significant directional presentation in specific stimulus distribution and direction combinations, with red cells indicating adjusted standardized residuals greater than 1.96 ($p < 0.05$), suggesting these combinations were effective.

4 Discussion

The objective of this study is to present directional force sensations through a rotational skin-stretch distribution by selecting control rules according to the desired direction of presentation. The results from experiment 2 indicate that using only global or local approaches is not sufficient for presenting stimuli in the desired directions used in this experiment. However, by applying a global approach for the front and back directions and a local approach for the other directions, it is possible to present directional stimuli for all conditions except upward. Although the accuracy was reduced because the skin was not directly stretched in a specified direction, the direction can be perceived from the distortion distribution of the rotation.

To present stimuli with consistent intensity and directionality, additional insights, including those obtained in this study, are necessary. The perceived intensity model obtained from experiment 1 allowed the presentation of stimuli of equal intensity across different body parts. Furthermore, considering spatial summation[3] owing to spatial range differences in stimuli presented globally and locally is essential for designing stimuli that the entire hand can perceive. Thus, to use the proposed system for presenting directional stimuli with consistent intensity, it is crucial to design stimuli that consider both the perceptual intensity model of each body part and the differences in perceived intensity between global and local presentations.

In experiment 1, participants failed to perceive the stimuli for a 10° rotation. This can be attributed to the flexibility of the tactor material and torsion of the bracelet owing to the rotation of the tactor. Prior research with rotational skin-stretch stimuli presented to the forearm using a chloroprene rubber sponge as the tactor showed that subjects could respond to smaller rotation angles such as 12 and 6°[6]. By contrast, we used a gel with a relatively soft penetration index of 55(JIS K2207), which potentially absorbed most of the displacement and resulted in stimuli near the absolute threshold of perception. As the bracelet is not fixed, rotation of the tactor may cause torsion of the bracelet, attenuating the amount of skin deformation.

The results of experiment 2 showed that the correct response rate for the local rules was higher than that for the global rules. This may be because the participants perceived the position of the operating tactor, as in the studies by Hong et al. [5] and Stanley et al. [13]. However, a more detailed investigation is required to determine whether users can perceive the direction of tactile rotation, given the tendency to perceive the front-back direction in the global rule.

Skin-stretch devices typically include stationary parts that are fixed to the body in addition to their movable components. Devices for fingers[4] or arms[2] produce strain by presenting deformations through movable parts against these fixed sections. In experiment 1, only one tactor was moved while the others remained stationary, serving to anchor the device to the body. Conversely, in experiment 2, multiple tactors were simultaneously activated, potentially causing the entire device to move on the body.

Designing stimuli that consider the overall displacement and torque generation of the device remain a future challenge.

This study explored directional presentation along three axes. However, presenting directions between these axes remains a challenge. Interactions with real objects can produce forces in any direction, necessitating the presentation of forces that change direction continuously rather than presenting them discretely. Expanding the two sets of stimuli prepared for this study and adjusting the presented rotation angles could potentially allow for the presentation of diagonally directed stimuli. In addition, utilizing the concept of phantom sensation for positional information presentation, as proposed for vibration stimuli[10], can enable stimulus presentation between axes.

5 Conclusion

In this study, we propose a wearable system that presents the direction of force through rotational skin-stretch stimulus distribution to the wrist. The hardware designed for the wrist comprised four rotating tactors, each capable of independent control over the direction and angle of rotation. We introduce two control rules: global and local. Global stimulation distributes strain between two tactors or in front of and behind the tactors to indicate direction, whereas local stimulation uses a combination of two specific tactor rotations to locally create a strain distribution for direction indication. We conducted two experiments. The first verified each tactor's ability to present stimulus intensity using magnitude estimation, establishing a consistent model between rotation angle and perceived intensity. The second experiment involved a preliminary investigation of the ability of the system to present directional force-like sensations using the two proposed control rules. The results showed that global stimulation could present forward and backward directions, whereas local stimulation could present directions other than upward. This suggests that combining multiple control rules can implement the desired functionality, leading to the future exploration of continuous directional force changes between different axes.

Our system is lightweight, compact, and easily integrated with the XR content. We created interactions based on the stimulus distribution shown in Fig. 7, such as simulating the weight of virtual objects or a semi-static force sensation of being pulled by an object to enhance immersion. Furthermore, by intervening in tactile interactions with real objects, we implemented a tactile AR that alters mechanical properties such as weight. The palm-free design allows for interaction with real objects, seamlessly bridging real and virtual experiences, demonstrating the high potential of the system for XR content integration.

Acknowledgments. This work was supported by the JST Moonshot R&D Program "Cybernetic Being" Project (grant number JPMJMS2013) and JST ACT-X (grant number JPMJAX21KG). The experimental system was developed with the support of commissure Inc.

Disclosure of Interests. The authors declare no competing interests relevant to the contents of this article.

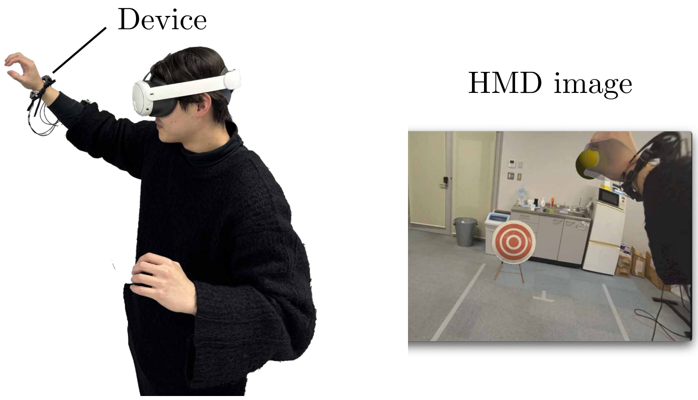


Fig. 7. Ball Throwing Interaction

References

1. Bark, K., Wheeler, J., Shull, P., Savall, J., Cutkosky, M.: Rotational skin stretch feedback: A wearable haptic display for motion. IEEE Transactions on Haptics **3**(3), 166–176 (2010). https://doi.org/10.1109/TOH.2010.21
2. Chinello, F., Pacchierotti, C., Bimbo, J., Tsagarakis, N.G., Prattichizzo, D.: Design and evaluation of a wearable skin stretch device for haptic guidance. IEEE Robotics and Automation Letters **3**(1), 524–531 (2018). https://doi.org/10.1109/LRA.2017.2766244
3. Gescheider, G.A., GüÇlü, B., Sexton, J.L., Karalunas, S., Fontana, A.: Spatial summation in the tactile sensory system: Probability summation and neural integration. Somatosensory & motor research **22**(4), 255–268 (2005)
4. Gleeson, B.T., Horschel, S.K., Provancher, W.R.: Design of a fingertip-mounted tactile display with tangential skin displacement feedback. IEEE Transactions on Haptics **3**(4), 297–301 (2010)
5. Hong, J., Pradhan, A., Froehlich, J.E., Findlater, L.: Evaluating wrist-based haptic feedback for non-visual target finding and path tracing on a 2d surface. In: Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility. p. 210–219. ASSETS '17, Association for Computing Machinery, New York, NY, USA (2017). https://doi.org/10.1145/3132525.3132538, https://doi.org/10.1145/3132525.3132538
6. Horie, A., Kashino, Z., Shimobayashi, H., Inami, M.: Two-dimensional moving phantom sensation created by rotational skin stretch distribution. In: 2021 IEEE World Haptics Conference (WHC). pp. 139–144 (2021). https://doi.org/10.1109/WHC49131.2021.9517252
7. Horie, A., Zheng, Y., Inami, M.: A wearable system integrating force myography and skin stretch feedback toward force skill learning. In: 2023 IEEE World Haptics Conference (WHC). pp. 190–196 (2023). https://doi.org/10.1109/WHC56415.2023.10224440
8. Kameoka, T., Kajimoto, H.: Tactile transfer of finger information through suction tactile sensation in hmds. In: 2021 IEEE World Haptics Conference (WHC). pp. 949–954 (2021). https://doi.org/10.1109/WHC49131.2021.9517176
9. Moriyama, T., Kajimoto, H.: Wearable haptic device presenting sensations of fingertips to the forearm. IEEE Transactions on Haptics **15**(1), 91–96 (2022). https://doi.org/10.1109/TOH.2022.3143663

10. Ohara, G., Kikuchi, D., Konyo, M., Tadokoro, S.: Stereohaptic vibration: Out-of-body localization of virtual vibration source through multiple vibrotactile stimuli on the forearms. IEEE Transactions on Haptics (2024)
11. Perret, J., Vander Poorten, E.: Touching virtual reality: a review of haptic gloves. In: ACTUATOR 2018; 16th International Conference on New Actuators. pp. 1–5. VDE (2018)
12. Pezent, E., Gupta, A., Duhaime, H., O'Malley, M., Israr, A., Samad, M., Robinson, S., Agarwal, P., Benko, H., Colonnese, N.: Explorations of wrist haptic feedback for ar/vr interactions with tasbi. In: Adjunct Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology. UIST '22 Adjunct, Association for Computing Machinery, New York, NY, USA (2022). https://doi.org/10.1145/3526114.3558658, https://doi.org/10.1145/3526114.3558658
13. Stanley, A.A., Kuchenbecker, K.J.: Evaluation of tactile feedback methods for wrist rotation guidance. IEEE Transactions on Haptics **5**(3), 240–251 (2012). https://doi.org/10.1109/TOH.2012.33