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Design and Validation of Pseudo-Force Haptic Device for Actual Walking

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***Abstract*— Pedestrian navigation systems on smartphones have become integral to modern society. However, a crucial problem in pedestrian navigation is that visual and/or auditory cues can distract situational awareness while walking, which may lead to serious consequences. To address this problem, various haptic navigation devices have been developed. Among these, a pseudo-force sensation elicited by asymmetric vibrations on the skin is considered a promising method owing to its intuitive directional cues. Nevertheless, pseudo-force sensation for pedestrian navigation has yet to be well validated in actual walking situations. Here, we propose an untethered pseudo-force haptic device for pedestrian navigation. Our device controls the direction of pseudo-force sensation by delivering asymmetric vibrations to the fingertips using a pair of vibrotactile actuators. Perceptual and navigation experiments were conducted to examine the effectiveness of the proposed pseudo-force navigation device. Our results suggest that pseudo-force navigation is effective during actual walking.**

I. INTRODUCTION

Pedestrian navigation has become a popular service in modern society. Typical pedestrian navigation on smartphones uses visual, auditory, or a combination of both cues to provide turn-by-turn direction. Pedestrian navigation systems facilitate finding paths in unfamiliar environments or unexplored places.

However, a crucial problem with pedestrian navigation is that visual and/or auditory cues can distract situational awareness while walking, which may lead to serious consequences. There are scenarios in which individuals may become preoccupied while traversing busy avenues, appreciating picturesque landscapes, or engaging in conversations. Each time users use the system for pedestrian navigation, they are deprived of their visual and auditory senses and become immersed in operating their smartphones, oblivious to their surroundings and others. This heightened immersion from smartphone operation increases the likelihood of mishandling and inadvertent encounters and isolates the user from real-life social interactions.

To address this problem, many haptic navigation devices have been proposed. Prior haptic navigation research focused on vibrational cues, which are prioritized for cost-effectiveness, portability, and low power usage. These vibrational cues can be broadly divided into two categories: those that encode and convey patterns of vibrational frequency and intensity [1], [2], [3], [4], [5], [6], [7] and those that rely on the location of the vibration [8], [9]. Several vibrational cues are integrated into contemporary smartphones and wearable navigation technologies. However, recognizing vibrational cues can be challenging given the short duration required to identify vibration patterns and the close distance between multiple actuators.

Fig. 1. Waylet is an untethered haptic device that employs asymmetric vibrations to provide translational and rotational pseudo-force directional cues for pedestrian navigation.

To provide intuitive directional haptic cues, pseudo-force sensations elicited by asymmetric vibrations of the skin have been introduced. Amemiya et al. [10] pioneered a pseudo-force system using a slider-crank mechanism. Subsequently, Amemiya et al. [11] applied this mechanism to achieve a two-dimensional pseudo-force sensation. Rekimoto [12] realized that a linear resonant actuator, which is a more compact alternative to the previous methods, can generate a pseudo-force sensation [10], [11]. Amemiya et al.[13] further developed a comparable system using voice-coil actuators. Subsequent devices enabled both translational and rotational pseudo-force sensations by placing two vibrotactile actuators [14], [15]. In addition, a pseudo-force sensation is enhanced by body movements [16]. This feature also indicates that pseudo-force sensation is suitable for pedestrian navigation.

Nevertheless, a pseudo-force sensation for pedestrian navigation has yet to be well-validated in actual walking situations. As elucidated in a comprehensive review by Kappers et al. [17], the majority of haptic navigation investigations assessed the capacity for haptic directive recognition or per-

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ceptual attributes instead of concentrating on actual walking navigation. This limitation is predominantly because of the reliance of devices on sizable actuators and external power reservoirs [18]. In fact, several lines of study [11], [14], [15] have achieved multidimensional pseudo-force sensations; however, these methods incorporate large actuators or rely on an external apparatus for power supply and control. This presents a significant challenge, particularly in scenarios that permit unrestrained user mobility. In other words, while a method has been developed to provide multi-dimensional pseudo-forces, a device capable of reproducing pseudo-forces for actual walking experiences has yet to be developed.

Thus, we proposed an untethered pseudo-force haptic device, called Waylet [19], for pedestrian navigation (Fig. 1). Our device controls the direction of a pseudo-force sensation by delivering asymmetric vibrations to the fingertips using a pair of vibrotactile actuators. Compared with previous devices [14], [15], our device is characterized by being pocket-sized, untethered, and having an all-in-one package. Moreover, our device can stably generate a pseudo-force sensation without adding an unnecessary mass to the fingertip. We presented a preliminary system and concept at a conference, and demonstrated the Waylet system [19].

In this study, we tested our device in a mixed-reality (MR) environment. This test environment has the advantage of providing accurate location data unencumbered by global positioning system (GPS) precision constraints, enabling the evaluation of haptic navigation systems in actual walking scenarios.

The contributions of this study are as follows:

- Designed an untethered haptic device that can provide translational and rotational pseudo-force sensation.
- Revealed the learning process of pseudo-force sensation through a perceptual experiment.
- Demonstrated the effectiveness of our pseudo-force navigation device during actual walking in an MR environment.

II. DESIGN AND IMPLEMENTATION

Although various grasping methods are available for haptic devices, we focused on grasping the index, middle, and thumbs. Pseudo-forces using asymmetric vibrations are most effectively perceived at the fingertips [14], [15], [20], where the density of mechanoreceptors is higher [21]. To ensure that the proposed device works reliably in actual walking scenarios, we established the following design requirements:

- Lightweight: Given subtle pseudo-forces using asymmetric vibrations [20], avoiding adding unwanted weight to the fingertips is crucial. The housing anchors to the palm, which possesses fewer mechanoreceptors than the fingertips. This approach minimizes added weight to the fingertips, facilitating effective pseudo forces.
- Alignment: The index finger and thumb should align in parallel for consistent pseudo-force using asymmetric vibrations [14], [20]. Any misalignment might lead to confusion and unintended torque.
- Distance between actuators: The distance between vibrotactile actuators is necessary to create the sensation of rotational pseudo-force [15].

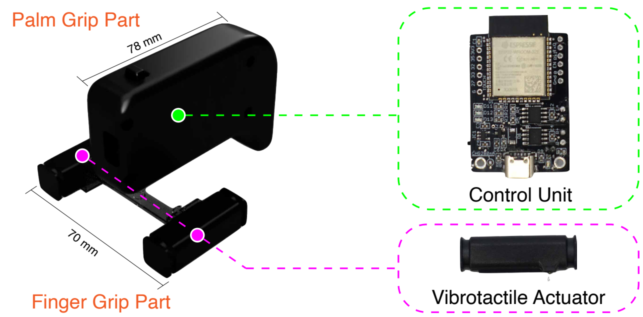

Fig. 2. Hardware. Our haptic device consists of vibrotactile actuators (finger grip part) and a control unit (palm grip part), including a circuit, battery, and wireless communication module, and the housing was made with an optical 3D printer.

A. Hardware

Our device weighed approximately 80 g and consisted of two vibrotactile actuators (finger-grip part) and a control unit (palm-grip part), including a circuit, battery, and wireless communication module (Fig. 2). For convenience, the housing was designed to be sufficiently compact using a single hand and printed by an optical 3D printer (J55, Stratasys, Material: VeroUltra). The device was controlled using Bluetooth or Wi-Fi. The device was operated continuously for approximately 60 min at the full charge rate.

Because pseudo-forces using asymmetric vibrations have a low force perception [12], we adopted a method in which the thumb holds one vibrotactile actuator, the index and middle fingers hold the other vibrotactile actuator, and the other fingers hold the grasping component. By grounding the control unit on the palm, no unwanted mass was added to the fingertips, and robust pseudo-forces were presented to the fingertips.

The vibrotactile actuator is a compact and lightweight voice coil actuator (HapCoil-One, Tactile Labs) capable of providing high-output vibrotactile stimuli. To avoid generating unwanted torque sensations, two vibrotactile actuators were fixed parallel to a thin flat plate. Referring to previous studies [14], [20], the distance between the two transducers was set to 70 mm. Ideally, the vibrations from the two actuators should be distinct. However, similar to previous studies [14], [20], we did not focus on isolating these vibrations in our approach.

The control unit mainly consisted of a microcontroller (ESP32, Espressif Systems Pte. Ltd.), wireless communication module, digital audio amplifier (NS4168, Shenzhenshi YONGFUKANG Technology co., LTD.), and battery (Data Power Technology, 500 mAh). A digital-analog converter (DAC) in the microcontroller generates stimulation.

B. Principle of Translational and Rotational Pseudo-Force

Based on the previous study by Tanabe et al. [14], translational and rotational pseudo-forces were induced by controlling the direction of the asymmetric vibrations input to the two actuators (Fig. 3a) and (Fig. 3b), respectively. When subjected to upward asymmetric vibrations(Fig. 3c, red line), the actuators generated forward pseudo-force-directional cues (Fig. 3a, red arrows). Conversely, backward pseudo-directional cues were generated (Fig. 3b, blue arrow) in response to the downward asymmetric vibrations (Fig. 3d, blue line). Waylet can provide rotational pseudo-forces by changing the combination of force directions exerted by each vibrotactile actuator (Fig. 3b).

III. EXPERIMENT

We evaluated our haptic device through perceptual and navigational experiments. In the perception experiment, we measured the correct answer rates for pseudo-force directions generated by our device. In the navigation experiment, we examined the navigation task performance of our device in the MR environment. In both experiments, we employed another type of information presentation using vibration patterns as a baseline method for comparison, in which the navigation directions (forward, backward, leftward, and rightward) were encoded with four different vibrational patterns [6]. This is a more symbolic presentation of information than the intuitive pseudo-force sensation, a method that can be reproduced on a single device and applied to actual walking navigation. All the participants completed the two experiments in less than two hours.

A. Participants

Ten healthy adults (five female) voluntarily participated in the experiment. All the participants received financial compensation for their participation. The mean age was 32.1 $\pm$ 8.9 years. According to the self-reports, all participants were right-handed. Additionally, none of the participants had experienced any haptic devices during their research and development. The experimental protocol was approved by the institutional review board of Toyota Central R&D Labs., Inc.

B. Haptic Directional Cues

1) Pseudo-Force: Based on previous studies [12], [22], a 40 Hz asymmetry square waveform (duty ratio = 1:4) [12] with a maximum acceleration amplitude of approximately 120 m/s^2 [22] was utilized to generate a pseudo-force sensation (Figs. 3c, 3d). The device can generate forward, backward, leftward, and rightward pseudo-force sensations by controlling two actuators, as shown in Figs. 3a, 3b.

2) Vibration Pattern: The vibrational pattern was determined by using the two-pulse encoding method proposed by Pielot et al. [6] (Fig. 3e). Specifically, directions were encoded by timing and the number of blanks inserted in the 40 Hz symmetry square waveform (duty ratio = 1:1) for 1 s, as shown in Fig. 3f). Two actuators were driven simultaneously in order to match the stimulus intensity as closely as possible with the pseudo-force method. In this method, forward stimuli were presented twice at equal time intervals. Similarly, backward stimuli were introduced three times, also at consistent intervals. The leftward stimuli were used in a sequence of long vibrations followed by short vibrations. Conversely, the rightward stimuli were used in a sequence of short vibrations followed by long vibrations.

C. Perceptual Experiment

1) Objective: To reveal the learning process of haptic directional cues, we measured the correct answer rates for the haptic directional cues. We hypothesized that the correct answer rates of a pseudo-force sensation would improve more quickly and achieve better performance than the vibration pattern. This hypothesis was based on the idea that, compared to the vibration pattern, a pseudo-force sensation elicited by asymmetric vibrations is more intuitive, and therefore, easier to learn.

2) Procedure: Participants sat on a chair and received a paper describing the vibration stimuli used (Fig. 4). Additionally, they wore noise-canceling earphones (AirPods Pro, Apple Inc.) and heard white noise throughout the experiment. Therefore, they were not given any auditory cues/indications. They were then asked to lightly pinch the vibrotactile actuators of our device with their index, middle, and thumb fingers and to hold the palm-grip part with their other fingers. For each trial, the participants were instructed to lower their hands in an initial position but were allowed to move their hands during the stimulation presentation. When the stimulation ended, participants were required to verbally answer which stimuli were presented using a four-alternative forced choice method (forward, backward, leftward, or rightward). The experimenter then gave the participants feedback on whether the answer was correct or incorrect. In each block, four types of stimuli were randomly presented five times (20 trials per block). The block was repeated six times with a one-minute break in between.

Note that, in this perceptual experiment, the participants experienced haptic stimulation with our device for the first time because no practice session was provided prior to the experiment. In addition, to minimize order effects, the order of stimulation types (i.e., pseudo-force and vibration patterns) was counterbalanced across participants.

3) Results: One participant (P5) had no sense of a pseudo-force and showed no improvement throughout the experiment (mean correct answer rate, 32%; green stars in Figs. 5a, 5b). Therefore, this participant was excluded from the subsequent analyses, and the remaining nine participants were included in the statistical analysis.

We performed the Kruskal-Wallis test to examine the learning process of correct answer rates for each haptic cue. The threshold for statistical significance was set at $\alpha < 0.05$. The Kruskal-Wallis test revealed no significant main effect from the block on either pseudo-force ($p = 0.73$; Fig. 5a) or vibration pattern ($p = 0.99$; Fig. 5b) conditions. These results suggest that although subtle improvements were observed during early blocks in the pseudo-force condition, users

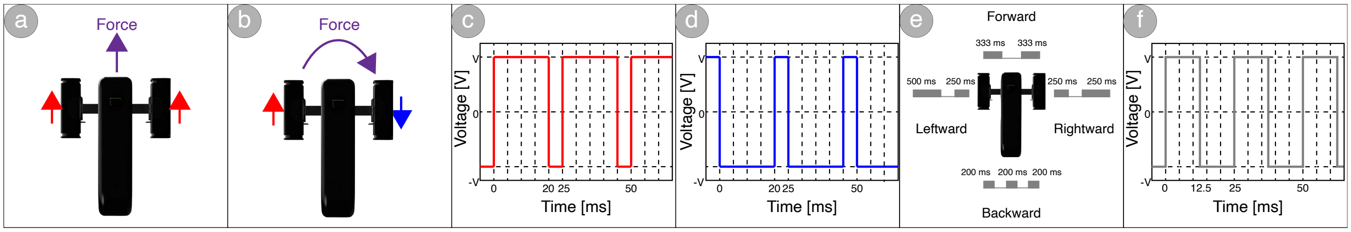

Fig. 3. Haptic feedback method. Principle of (a) translational and (b) rotational pseudo-forces. (c) Upward asymmetric vibrations. (d) Downward asymmetric vibrations. (e) Vibration pattern method using two-pulse encoding. (f) Symmetric vibrations.

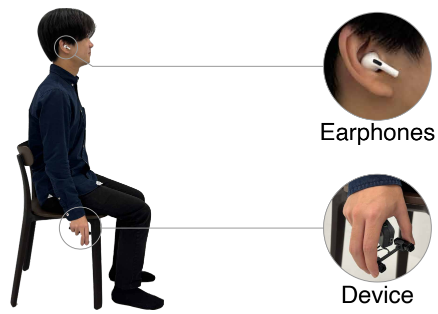

Fig. 4. Experimental setup for perceptual experiment. Participants sat in the chair, held the device, and wore the noise-canceling earphones.

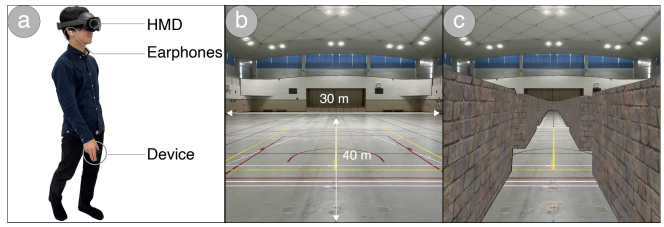

Fig. 6. Experiment setup for the navigation experiment. Participants held the device with their right hand, and wore the noise-canceling earphones and the HMD (a). The experiment was conducted in the gymnasium (b). Participants walked around the gymnasium, wherein a virtual maze was reconstructed (c).

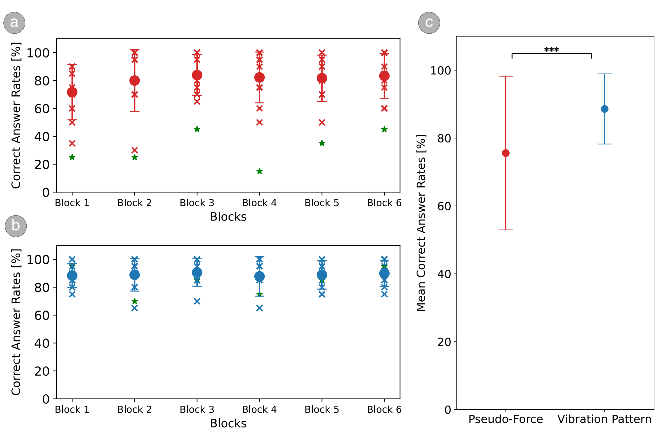

Fig. 5. Results of perceptual experiment. (a) Correct answer rates of the pseudo-force condition. (b) Correct answer rates of the vibration pattern condition. In (a) and (b), the bar graphs indicate all participants' mean correct answer rates and the error bars show the standard deviation except P5. The green plots indicate the correct answer rates of P5. (c) Mean correct answer rates of all participants with the accompanying standard deviation.

could understand haptic directional cues in any form without much effort.

Next, we compared the mean correct answer rates between the two conditions using a paired t-test. The results showed that the correct answer rate was significantly better in the vibration pattern condition than in the pseudo-force condition ($p = 0.001$; Fig. 5c). This suggests that contrary to expectations, users can more easily understand the haptic directional cues encoded in the vibration patterns.

D. Navigation Experiment

1) Objective: We conducted an experiment to examine the effectiveness of a pseudo-force sensation in pedestrian navigation during actual walking. We hypothesized that the participants would navigate faster to the goal in the pseudo-force condition than in the vibration-pattern condition. This hypothesis is based on the belief that an intuitive directional cue provided by a pseudo-force sensation results in more effective navigation.

2) Apparatus: A previous outdoor navigation experiment reported that inaccurate GPS signals and their delays lead to confusion [23]. To address this limitation, a novel test environment is constructed for pedestrian navigation. Specifically, we relied on the precise self-positioning function of the Meta Quest Pro HMD (Meta Platform Inc.) (Fig. 6a). This HMD can estimate the user position data using a built-in camera and inertial measurement units without any additional external sensors. We preliminarily confirmed that the position estimation accuracy was within a few centimeters.

The experiment was conducted in a gymnasium approximately 40×30 m^2 (Fig. 6b). In this space, we reconstructed a virtual maze using Unreal Engine 5.1.1 (Fig. 6c). For the navigation experiment, we created four different routes with path lengths of 60 m (Fig. 7). The participants walked in this maze according to haptic directional cues. The haptic directional cues were presented 2 m before each intersection. When the participant stood still, the cue was repeated every 2 s. In addition, when participants took the wrong route, a backward cue was presented, and the participants returned to their previous positions.

3) Procedure: Prior to commencing the navigation experiment, the participants relearned haptic directional cues

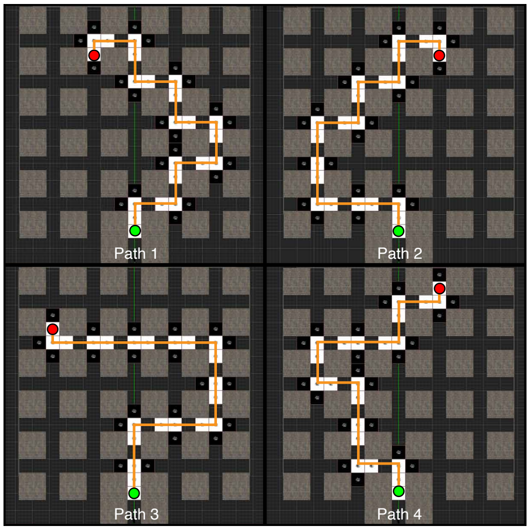

Fig. 7. Four routes used in the navigation experiment. Orange lines denote the navigated routes. Green and red dots represent the start and goal points of each route, respectively. White bars indicate areas where haptic directional cues are presented.

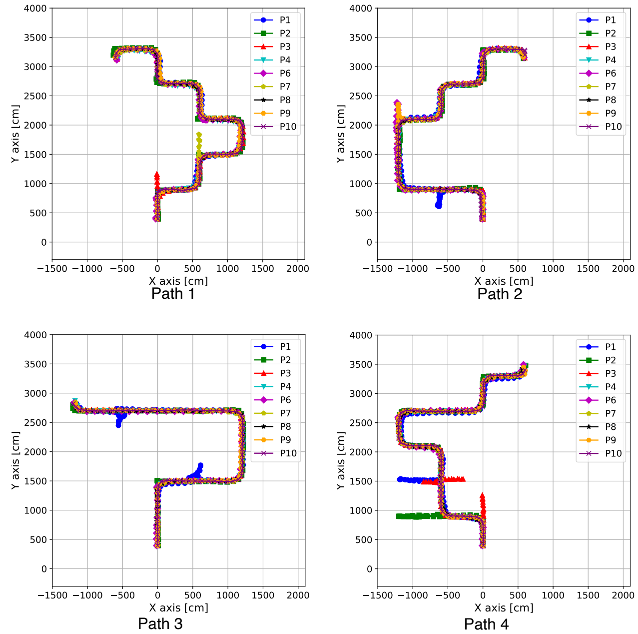

Fig. 8. Results of pseudo-force condition in the navigation experiment, showing the paths (path 1 to path 4) for each of the nine participants (except P5).

to minimize learning differences between the two methods. Next, participants underwent a practice session to familiarize themselves with walking through the virtual maze while wearing the device (Figure 6a). At this session, one participant (P5) was unable to participate in the navigation experiment. The inability to participate was due to P5's inability to perceive haptic directional cues. Consequently, they could not successfully complete the practice session tasks within the allotted experimental time.

Subsequently, the participants were instructed to walk on each of the four routes according to the haptic directional cues. A rest break of approximately 3 min was allowed between trials. This procedure was repeated twice under different cue conditions (i.e., pseudo-force and vibration pattern). To minimize the order effect, the order of the two conditions was counterbalanced across participants. After the navigation experiment, participants were also asked to complete a questionnaire [24] regarding the subjective evaluation of the haptic directional cues for each condition. The questionnaire consisted of 12 items rated on a 5-point Likert scale (1 = strongly disagree, 3 = neutral, 5 = strongly agree).

4) Results: Figs. 8 and 9 show the trajectories in which the participants walked under the pseudo-force and vibration pattern conditions, respectively. All participants were able to reach the goal on every route, although they sometimes took the wrong directions. There were 13 incorrect directions in the pseudo-force condition and 33 in the vibration pattern condition, suggesting the superiority of pseudo-force navigation in actual walking situations.

Regarding the elapsed time for arrival, there was a clear tendency for the pseudo-force condition to be shorter than that for the vibrational pattern condition (Fig. 10). In fact, the mean elapsed time to arrive, averaged across the routes, was significantly shorter in the pseudo-force condition than in the vibration-pattern condition (79.5 $\pm$ 18.7 s *vs.* 117.2 $\pm$ 51.3 s; $p = 0.0003$, Welch t-test). This result also suggests that the pseudo-force is advantageous as a haptic directional cue in actual walking.

5) Subjective Evaluation: Table. I shows the results of the comparisons of subjective evaluation scores between the two cue conditions. Although a Welch t-test was performed for each questionnaire item, no significant difference in the scores was found between the conditions ($p > 0.1$).

Comments regarding the pseudo-force conditions were generally positive. Participants expressed their opinions with phrases, such as "I found the cue was intuitive and clear" and "While in the perceptual experiment, haptic directional cues were difficult to understand, in the navigation experiment, I perceived a pseudo-force more clearly and was able to move smoothly." In contrast, participant P5, who could not perceive a pseudo-force reported, "I found it difficult because all vibrations felt the same, and I could not distinguish directions at all."

Conversely, comments on the vibration pattern conditions highlight some challenges. Participants expressed their opinions with phrases, such as "Distinguishing between leftward and rightward was clear, but discerning forward and leftward was tough" and "Continuous vibration cues were hard to track, which lead to confusion during walking." Some added, "While sitting, the vibrations were noticeable, but walking made it difficult to understand," and "Once I lost the vibration sequence, decision-making became challenging."

IV. DISCUSSIONS

A. Perceptual Experiment

In the perceptual experiment, we did not find any learning effects in either the pseudo-force or vibration pattern

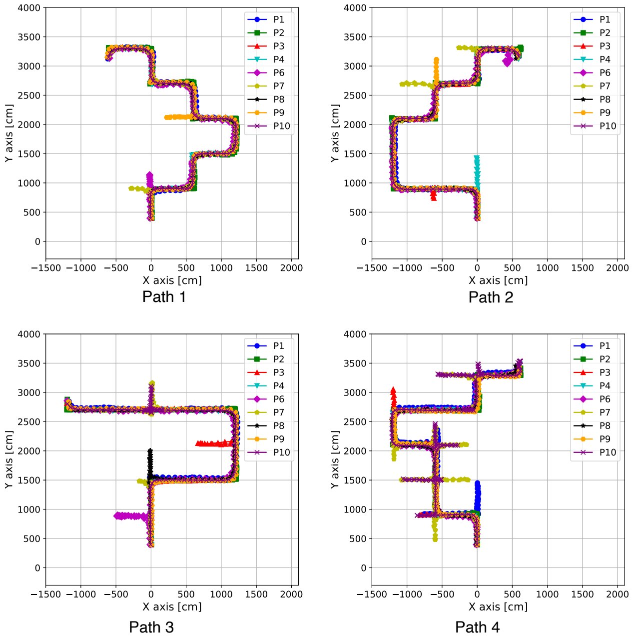

Fig. 9. Results of vibration pattern condition in the navigation experiment, showing the paths for each of the nine participants (except P5).

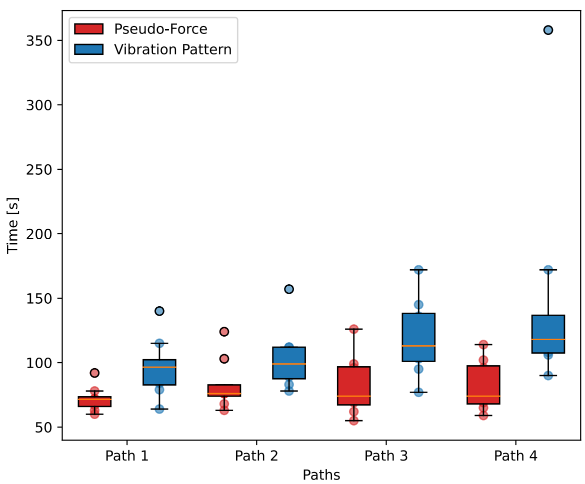

Fig. 10. Results of navigation experiments. Boxplot showing arrival time taken by the haptic device to arrive at various paths (path 1 to path 4) using pseudo-force (red) and vibration pattern (blue).

conditions. In addition, the mean correct answer rate under the vibration pattern condition was higher than that under the pseudo-force condition. Contrary to our expectations, directional cues encoded in vibration patterns seem to be clearly distinguishable, even for the first time. While a pseudo-force sensation is considered to be more intuitive, the symbolic presentation of the vibration pattern was immediately understood and recognized by the participants. This may be a testament to the adaptability of the human sensory system and its ability to connect new sensory cues with predefined meanings quickly.

Interestingly, one participant could not perceive a pseudo-force sensation throughout the experiment. Such remarkable individual differences in sensation may provide new insights into the mechanisms underlying pseudo-force sensation elicited by asymmetric vibrations. Although a pseudo-force sensation has been researched for a long time, its underlying mechanisms are not fully understood. Investigating the impact of individual differences on pseudo-force sensation is an interesting future research direction.

TABLE I

RESULTS OF COMPARISONS OF SUBJECTIVE EVALUATION SCORES BETWEEN THE PSEUDO-FORCE AND VIBRATION PATTERN CONDITIONS

Question	Pseudo-Force	Vibration Pattern	P-Value
Using the device was confusing	$1.56{\pm}0.49$	$1.67{\pm}0.67$	0.83
I found the experiment physically tiring	$1.11{\pm}0.31$	$1.22{\pm}0.42$	0.69
I found the experiment mentally tiring	$1.11{\pm}0.31$	$1.44{\pm}0.68$	0.40
Left/right was easy to interpret	$4.22{\pm}0.79$	$3.44{\pm}1.17$	0.19
Forward/backward was easy to interpret	$4.44{\pm}0.68$	$4.00{\pm}0.82$	0.27
Combined instructions were easy to interpret	$3.78{\pm}1.03$	$3.56{\pm}0.68$	0.63
I enjoyed using the device	$4.56{\pm}0.50$	$4.33{\pm}0.47$	0.43
I found the device annoying	$2.00{\pm}1.05$	$2.22{\pm}1.31$	0.79
I felt I could trust the device	$4.22{\pm}0.63$	$4.11{\pm}0.74$	0.79
I felt like the instructions were precise	$4.33{\pm}0.67$	$4.33{\pm}0.67$	1.00
I would like to try being guided while walking	$4.67{\pm}0.67$	$4.22{\pm}1.03$	0.40
I feel like it could guide me in an urban situation	$4.11{\pm}0.87$	$3.55{\pm}1.17$	0.33

B. Navigation Experiment

Unlike the perceptual experiment, the navigation experiment demonstrated the superiority of the pseudo-force directional cues in terms of the elapsed time to arrive. This may be because intuitive pseudo-force navigation requires less effort to make decisions regarding the directions at each intersection. This result supports our hypothesis that the pseudo-force provides intuitive directional cues that are useful for turn-by-turn pedestrian navigation. Furthermore, this result supports the view presented in the previous research by Yoshida et al. [25], which concluded that cognitive activities increase the vibration response time.

Surprisingly, pseudo-force navigation was also better in terms of the number of errors compared to navigation with vibration patterns. This was the opposite of the results of the perceptual experiment and was first revealed through testing in actual walking situations. Based on the results of perceptual experiments, haptic devices are often inferred to be useful for navigation. However, as the systematic review by Kappers et al. [17] indicated, validation in actual walking environments is indispensable for determining the applicability of haptic devices to pedestrian navigation. The MR test environment developed in this study is a powerful tool for this purpose.

V. CONCLUSIONS

In this study, we proposed a pseudo-force haptic device using asymmetric vibration and conducted both perceptual and navigation experiments. The results of the perceptual experiment highlighted the superior correct answer rates of the vibration pattern condition. However, during the navigation experiments, the pseudo-force condition led to more intuitive navigation and quicker destination arrival than the vibration pattern condition. These results suggest that the pseudo-force condition is suitable for haptic navigation in an actual walking scenario despite the limitations of MR environments. We anticipate that our device will be integrated with future haptic navigation services in outdoor environments.

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