Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

Research and Design of Guidance Products Based on Vibrotactile Phantom Sensations

Xueqin Li, Weizi Xu

How to cite: Li X, Xu W. Research and Design of Guidance Products Based on Vibrotactile Phantom Sensations. Textile & Leather Review. 2026; 9:6229-6249. https://doi.org/10.31881/TLR.2026.6229

How to link: https://doi.org/10.31881/TLR.2026.6229

Published: 24 November 2026

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License

Research and Design of Guidance Products Based on Vibro-tactile Phantom Sensations

Xueqin Li, Weizi Xu*

School of Mechanical Engineering and Automation BUAA, Beihang University, Changping 100191, Beijjng, China
*r2591338519@163.com

Article
https://doi.org/10.31881/TLR.2026.6229
Published 24 November 2026

ABSTRACT

Traditional tactile guidance methods often struggle to provide precise directional cues in complex environments and may impose excessive cognitive load on users, necessitating the integration of advanced textile sensors and haptic actuators into wearable fabrics for more intuitive feedback. To address these limitations, this study proposes a wearable guidance approach based on phantom tactile vibration feedback and examines its feasibility within human–computer interaction contexts. The study first quantified the absolute and difference thresholds of wrist-based vibration perception, establishing parameter boundaries necessary for effective feedback encoding. Building upon these results, a direction recognition experiment employing phantom tactile stimulation was conducted to compare multiple encoding strategies in terms of directional accuracy and perceptual continuity. Leveraging the experimental findings, a wearable guidance device concept was further developed and demonstrated within a metro station entry scenario. The outcomes confirm the feasibility of applying phantom tactile feedback to wearable directional guidance and yield an integrated research framework encompassing tactile parameter modeling, interaction encoding strategies, and product-level structural design. This research contributes methodological insight for improving tactile user experience and provides theoretical and practical support for advancing accessible design and wearable interaction technologies integrated into smart textile systems. By embedding haptic feedback mechanisms directly into functional fibers, these findings facilitate the development of more intuitive and responsive textile-based interfaces for diverse user needs.

KEYWORDS

phantom tactile sensation, human-computer interaction, user experience, accessibility design, textile systems

INTRODUCTION

People with visual impairments frequently encounter difficulties in wayfinding during independent mobility, particularly in complex indoor environments such as metro stations [1,2]. These constraints often result in a dependence on human guides, undermining user autonomy. While auditory guidance is common, its effec-

tiveness diminishes in noisy settings due to sound masking, information delay, and high cognitive load [3]. Consequently, the tactile channel—characterized by privacy, directness, and strong resistance to interference—has emerged as a vital alternative for conveying spatial information. Among various tactile modalities, vibration is widely used in engineered systems due to its effectiveness in delivering directional cues [4,5].

Reflecting this potential, a body of research has explored encoding vibration cues into directional information to aid visually impaired individuals. For example, systems have provided vibrotactile feedback to different fingertips to enhance indoor orientation [6], employed a waist belt with multiple motors to signal turning directions [7], or implemented multi-region tactile feedback for obstacle detection [8]. Similarly, research utilizing wearable vibration belts has demonstrated improved directional identification [9]. However, a dominant and limiting technical paradigm persists: most solutions seek to improve directional resolution by increasing the number of physical vibration actuators. This approach leads to increased hardware complexity, power consumption, and reduced wearability, while still failing to provide continuous guidance for arbitrary directions within a space [10,11].

To address these limitations, this study investigates phantom tactile sensation as an innovative alternative. This perceptual phenomenon occurs when two or more spatially separate vibration points are activated with specific intensity and timing relationships, causing the user to perceive a single, stable vibration at a “phantom” location between the physical actuators. This illusion enables the rendering of continuous directional cues and arbitrary locations using a minimal actuator array, offering a path toward high-resolution guidance without hardware redundancy.

Therefore, this research proposes, develops, and evaluates a wearable navigation system based on phantom tactile feedback. The work follows a structured methodology: first, the perceptual characteristics of the wrist are quantified through absolute and difference threshold experiments, establishing foundational parameters for stimulus design. Second, a direction recognition experiment evaluates and compares the accuracy and user experience of static (point-like) versus dynamic (moving) phantom tactile cues. Finally, these empirical findings are translated into a functional prototype design, demonstrated within a metro-entry scenario to showcase practical applicability.

This study contributes to the design of wearable navigation systems by demonstrating how phantom tactile encoding can achieve continuous directional guidance with a reduced number of actuators. By integrating

perceptual modeling with interaction design, the proposed approach offers a lightweight and scalable solution for vibrotactile navigation.

RELATED WORK AND THEORETICAL BACKGROUND

Phantom Tactile Sensation

Phantom tactile sensation refers to a tactile illusion perceived when two or more spatially separated vibration stimuli are delivered simultaneously or in sequence on the skin. Instead of perceiving the stimuli at their physical locations, the human somatosensory system integrates the signals and produces a perceived virtual point between them. This phenomenon was first described by Békésy in 1958, who identified the “funneling illusion,” demonstrating that users perceive a unified tactile sensation located between two stimuli of different amplitudes. The illusion becomes stronger when the spatial distance between vibration points is approximately 4 cm, revealing the sensitivity of mechanoreceptors in localized skin regions[12].

Later, Alles expanded the concept and formally introduced the term phantom sensation, proposing its use as a controllable feedback mechanism for prosthetic limb users[13]. His findings indicated that perceived phantom location can be modulated using amplitude and timing differences, where intensity manipulation produces a more distinguishable and stable virtual perception than timing modulation alone. These findings established phantom tactile feedback as an effective technique to generate continuous tactile cues without increasing the number of actuators.

Current research indicates that phantom touch can be regarded as a tactile encoding method based on tactile illusions, generating continuous spatial tactile information using a limited number of execution units, thereby providing higher information capacity and direction expression capabilities in tactile interactions. Currently, phantom touch has been applied in fields such as navigation, action guidance, and path tracking. For instance, Salazar et al. proposed a path guidance method based on phantom touch, using the principle of phantom touch to guide the wrist to move along a predetermined path, achieving precise guidance of a two-dimensional path, and having good auxiliary value for training hand movements [14]. Schäfer et al. compared two guidance methods in traditional vibration guidance: dynamically adjusting the intensity based on angle deviation and single-point feedback based on phantom touch. The conclusion proved that compared with the traditional single-point vibration, phantom touch provided higher direction recognition accuracy and smoother rotational guidance [15].

The perception of the position of the phantom touch point is influenced by multiple factors. In the vibration tactile interaction, the position of the phantom touch point is usually determined by the spatial positions and intensity ratios of adjacent vibration motors. For example, when the intensities of the two vibration stimuli are not consistent, the phantom touch point will lean towards the stronger stimulus point (Figure 1).

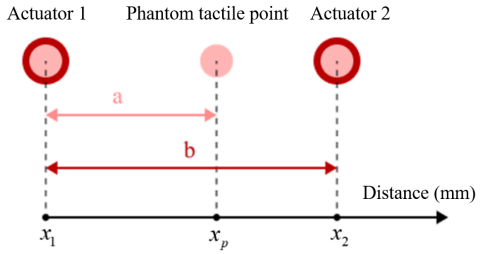

Figure 1. Schematic of the Phantom Tactile Sensation.

When Békésy first proposed the “funnel effect”, he also put forward a linear relationship formula between the intensity ratio and the position of the phantom contact point, as shown in Equation (1).

$$X_{phantom} = \frac{A_1 x_1 + A_2 x_2}{A_1 + A_2}$$

The variables in the equation are defined as follows: x_1 and x_2 represent the relative positions of the two vibration stimuli (in millimeters), while A_1 and A_2 denote the corresponding stimulus intensities (in volts). The linear weighting model does not account for the nonlinear response of the skin to vibratory energy. According to the physiological characteristics of Pacinian corpuscles, their perception is directly related to the vibratory energy and the square of the vibration amplitude. In 2011, Israr et al. extended the Pacinian-channel energy summation model and experimentally quantified the relationship between virtual-point perception and the intensity ratio of adjacent stimuli. Based on their findings, they proposed a set of equations (2)-(4) that more accurately describe the relationship between stimulus intensity and perceived phantom-point location in high-density vibrotactile arrays [16].

$$\beta = \frac{a}{b}$$

$$A_1 = \sqrt{1-\beta} \cdot A_{phantom}$$

$$A_2 = \sqrt{\beta} \cdot A_{phantom}$$

The variables in the equation are defined as follows: a denotes the relative distance between the first vibration actuator and the perceived phantom point (in millimeters), and b represents the distance between the two physical actuators (in millimeters). A_1 and A_2 correspond to the intensities of the two adjacent vibration stimuli (in volts).

Due to its strong alignment with the underlying physiological mechanisms, experimental reliability, and broad applicability, this model has become the prevailing theoretical foundation in the field of phantom tactile feedback. By incorporating the nonlinear response characteristics of the skin to vibratory energy, the model provides a more accurate description of the perceived phantom-point location. Accordingly, the subsequent experiments in this study adopt the energy-summation model proposed by Israr et al. based on the Pacinian channel as the theoretical basis. Combined with the tactile sensitivity characteristics of the wrist, this model supports the design of phantom-based guidance experiments and the development of the interaction system. The phantom tactile vibration feedback employed in this study is positioned as an interaction technology designed for spatial guidance through the tactile sensory channel. It functions within both the interaction-mechanism definition stage and the prototype verification stage of the design workflow. Unlike conventional approaches that rely on auditory cues or single-point vibration prompts, the present work incorporates the principle of phantom tactile sensation into a wearable guidance solution to address challenges such as auditory-channel overload in complex environments, difficulty in conveying continuous spatial direction, and insufficient cue resolution. Therefore, the technique serves not merely as an actuator-control strategy but as a fundamental mechanism shaping the functional logic and user experience of the guidance system. It provides a critical technical foundation for subsequent experimental design, parameter calibration, and prototype development.

Principle of Dynamic Guidance Based on Phantom Tactile Sensation

The core principle of phantom-tactile-based vibration guidance is to leverage perceptual illusions within the human tactile system. By coordinating the intensity and temporal patterns of multiple vibration actuators, a perceived “phantom point” is generated on the skin surface, enabling high-precision directional guidance.

This approach allows the system to render a virtual tactile sensation at locations where no physical actuator exists. In the remainder of this paper, this method is referred to as single-point phantom guidance.

The key technique involves computing the perceived phantom-point location using the energy-summation model and mapping the target direction to the coordinated activation of two adjacent actuators. Through this mechanism, any direction in the spatial domain can be conveyed to the user, thereby supporting continuous directional guidance (Figure 2).

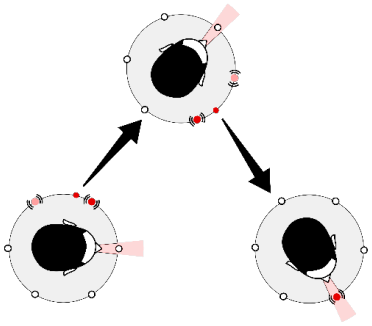

Figure 2. Schematic of vibration guidance by PTS.

However, although single-point phantom sensation overcomes the limitation of actuator count and improves directional resolution, its feedback remains inherently discrete. During actual movement, users receive directional cues only at key points, which may interrupt the flow of guidance. Such discontinuous feedback can increase cognitive load and is insufficient for smooth navigation in complex environments such as metro stations.

To address this limitation, this study further proposes a dynamic phantom guidance method based on the fundamental mechanism of single-point phantom sensation. By manipulating the temporal variation of vibration intensity, the perceived phantom point can be smoothly shifted along the skin surface, thereby providing continuous and intuitive directional cues. In the following sections, this method is referred to as dynamic phantom-based guidance. Its underlying principle is illustrated in Figure 3, where the horizontal axis represents time, the vertical axis denotes the perceived tactile position, and the color hue indicates the vibration intensity of each actuator at different time instances. M1 and M2 correspond to two adjacent vibration actuators.

Through this approach, the system can guide the user smoothly from their current orientation toward the target direction, enabling continuous directional feedback and enhancing the precision of the guidance process.

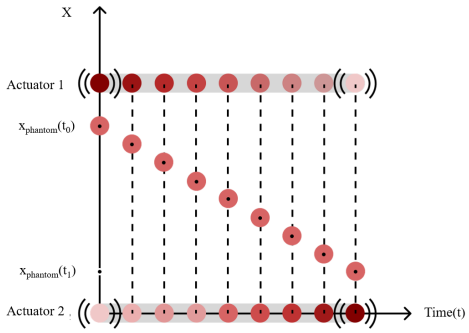

Figure 3. Schematic of the Apparent Tactile Motion.

PERCEPTUAL EXPERIMENTS AND PARAMETER MODELING FOR PHANTOM-BASED GUIDANCE

Experimental Design and Research Framework

This chapter conducts a series of perceptual experiments to investigate the applicability of phantom tactile sensation in wearable guidance systems. The objective is to examine whether phantom-based vibrotactile feedback can provide directional cues that are recognizable, stable, and continuous for users. To ensure scientific rigor and verifiability, the experimental procedure adopts a progressive, two-stage structure, forming a research chain that extends from fundamental perceptual measurement to applied validation.

Since the generation of phantom tactile sensation depends on vibration stimuli within an appropriate intensity range, insufficient stimulation may result in indistinct tactile perception, whereas excessive stimulation may cause discomfort or interfere with subsequent direction recognition. Therefore, before conducting the direction recognition experiment, it is necessary to determine the effective intensity range and difference threshold suitable for phantom-based encoding through a vibrotactile perception threshold experiment. The results serve as the foundation for configuring vibration parameters in the subsequent phantom-based experiments, ensuring that the stimuli remain perceivable and distinguishable, thereby improving the validity and reliability of direction recognition outcomes.

After establishing the foundational perceptual parameters, the study proceeds to the second stage: the direction recognition experiment based on phantom tactile feedback. This experiment aims to verify whether combinations of multi-point vibration stimuli can generate clear and distinguishable virtual tactile points on

the skin surface and whether these perceived points can be used to identify target directions. By introducing different tactile encoding strategies, the experiment further evaluates the usability, recognition accuracy, perceptual stability, and applicability of phantom-based guidance in dynamic scenarios.

Experimental Setup

Apparatus

The wearable guidance wristband was first modeled using 3D design software and subsequently fabricated as a physical prototype, as shown in Figure 4. The device consists primarily of six linear vibration motors, flexible materials for positional adjustment and strap tightening, and several 3D-printed structural components. The relationships among the components during operation are illustrated in Figure 5.

To minimize potential mechanical crosstalk between actuators, the wearable structure was designed to reduce unintended vibration transmission through the supporting materials. Specifically, only the active surfaces of the vibration motors were in direct contact with the skin, while the surrounding wristband and 3D-printed components were mechanically decoupled from the skin as much as possible. In addition, the actuators were slightly protruded from the supporting structure to limit the contact area between rigid components and the skin, thereby reducing vibration propagation through the device body. This design helps preserve the spatial distinctiveness of the vibrotactile stimuli and improves the perceptual clarity of the phantom tactile point.

During the experiment, an upper-computer interface was used to send control commands to an Arduino Uno microcontroller, which managed all vibration-motor functions and test operations.

The vibrotactile actuators used in the prototype were DJ1040 micro linear resonant actuators (LRAs) manufactured by Degkin Motor. The vibration intensity of each actuator was controlled via pulse-width modulation (PWM). According to the motor's technical specifications, the input voltage and resulting vibration amplitude exhibit a linear relationship. The actuator operates at a nominal frequency of 235 Hz, which is close to the peak sensitivity of Pacinian corpuscles at approximately 250 Hz—key mechanoreceptors responsible for perceiving high-frequency vibrations. This frequency alignment ensures that the actuator performance meets the requirements of the experiments.

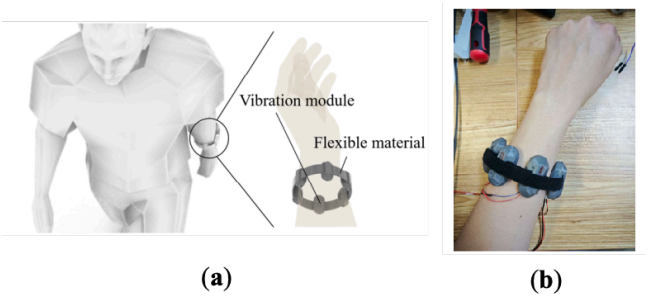

Figure 4. The prototype of this vibrating tactile wrist-worn device: (a) The three-dimensional model; (b) The physical prototype.

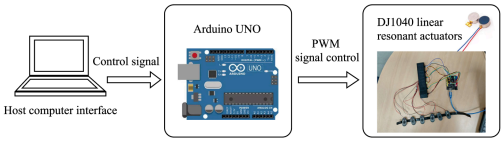

Figure 5. Relationship between components of the experimental device.

Experimental Procedure and Participant Information

A total of 10 participants were recruited for this study, all between 20 and 25 years of age. Individuals with tactile perception disorders or prior experience with similar experiments were excluded to ensure the objectivity of the results. Before the formal testing began, the vibration patterns and interaction procedures were explained to the participants. No abnormal physical reactions occurred during the experiment.

The experimental procedure was as follows:

1. The researcher provided a sign-in sheet and an informed consent form. Participants completed their basic demographic information, including name, gender, age, and experiment time, and signed the consent form.
2. During the preparation phase, participants were instructed to place their non-dominant hand (typically the left hand) steadily on the experimental platform. White-noise headphones were worn to prevent auditory interference caused by the vibration motors. The experimenter then assisted the participants in wearing the wristband device, adjusting strap tightness and actuator placement to ensure stable skin contact and consistent contact pressure between the wrist and vibration motors. The setup is illustrated in Figure 6.
3. Before starting the formal trials, all vibration motors were tested to ensure proper functioning, and participants were familiarized with the experimental tasks.
4. Different tasks were conducted depending on the specific experimental condition associated with each study.

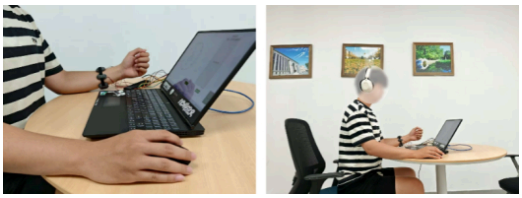

Figure 6. Experimental scenario.

Vibrotactile Perception Threshold Experiment on the Wrist

Objective

The wrist, as one of the tactilely sensitive areas of the human body, possesses relatively high spatial resolution and a rich distribution of mechanoreceptors, making it an ideal site for generating phantom tactile feedback[17]. In wearable guidance systems, the vibrotactile perception characteristics of the wrist directly influence the clarity of phantom tactile feedback and the accuracy of directional recognition. Therefore, before conducting phantom-based direction recognition experiments, it is necessary to determine the perceptual threshold range of vibration stimuli on the wrist. Establishing these thresholds ensures that subsequent stimulus parameters are both perceivable and comfortable, thereby preventing sensory fatigue or discomfort and providing quantifiable, controllable baseline parameters for the phantom tactile guidance system.

This experiment aims to measure two key parameters of wrist vibrotactile perception: the absolute threshold and the difference threshold. The absolute threshold identifies the minimum stimulus intensity required for participants to reliably perceive vibration, serving as a reference for defining the boundary between perceivable and non-perceivable stimuli in later experiments. The difference threshold represents the minimum detectable change in stimulus intensity that users can differentiate, indicating their sensitivity to vibration variation. By obtaining these two types of threshold data, the effective perceptual range of vibrotactile stimulation on the wrist can be established, providing a foundation for avoiding misperception, ambiguous feedback, or phantom errors in subsequent experiments.

Method

Fechner, a German psychophysicist, proposed three classical methods for quantifying perceptual thresholds: the method of limits, the method of constant stimuli, and the method of average error [18]. In this study, the method of limits was adopted to measure the absolute threshold, while the method of constant stimuli was used to determine the difference threshold (DL) by presenting comparison stimuli at predefined intensity levels relative to a standard stimulus.

For the absolute threshold experiment, the control board supplied a voltage of 5 V. Fifteen intensity levels were selected at 0.25 V intervals: 1.0 V, 1.25 V, 1.5 V, 1.75 V, 2.0 V, 2.25 V, 2.5 V, 2.75 V, 3.0 V, 3.25 V, 3.5 V, 3.75 V, 4.0 V, 4.25 V, and 4.5 V. Each vibration stimulus lasted for 1000 ms.

For the difference threshold experiment, a standard stimulus of 2.5 V was used. Comparison stimuli were set to the following intensities: 1.5 V, 1.75 V, 2.0 V, 2.25 V, 2.5 V, 2.75 V, 3.0 V, 3.25 V, 3.5 V, 3.75 V, and 4.0 V, with each stimulus lasting 1000 ms.

A customized control interface was developed using Python for this experiment. The testing interface for the absolute threshold experiment is shown in Figure 7, and it comprises three functional modules: an initial-voltage generation module, an amplitude-adjustment module, and a data-recording module. During the experiment, participants sequentially clicked the ten buttons in the initial-voltage generation module. After each vibration was triggered, they used the amplitude-adjustment module to determine the critical intensity at which the vibration became perceptible or imperceptible. The value was then saved using the recording module. After completing 10 trials, the researcher removed the wristband device, concluding the experiment. The interface for the difference threshold experiment is shown in Figure 8. Each comparison stimulus was paired with the standard stimulus for 50 trials.

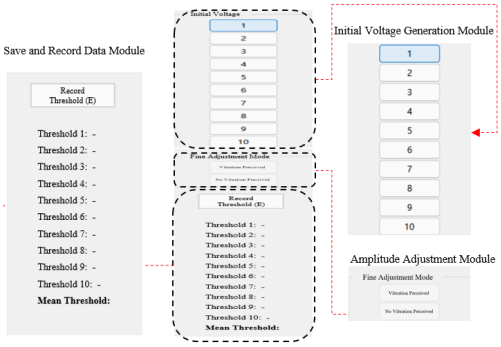

Figure 7. User Interface for the Absolute Threshold Experiment.



Figure 8. User Interface for the Difference Threshold Experiment.

Results and Analysis

A total of 100 data samples were collected in the absolute threshold experiment. The statistical distribution of the results is shown in Figure 9. The absolute thresholds were primarily concentrated around two adjacent critical intervals: 1.50–1.75 V and 1.75–2.00 V.

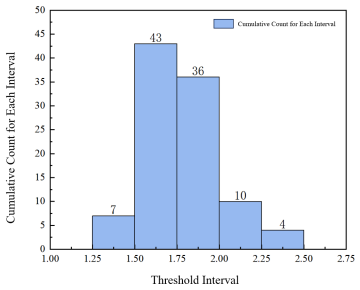

Figure 9. Histogram of statistical frequency distribution.

To determine the absolute threshold value, the mean was calculated based on the frequency distribution histogram:

$$\bar{x} = \frac{x_1 + x_2 + \cdots + x_n}{n} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

The absolute threshold was calculated as $M = \bar{x} = 1.778V$.

The comparison results obtained from the difference threshold experiment were then statistically analyzed, and the frequency distribution is shown in Figure 10.

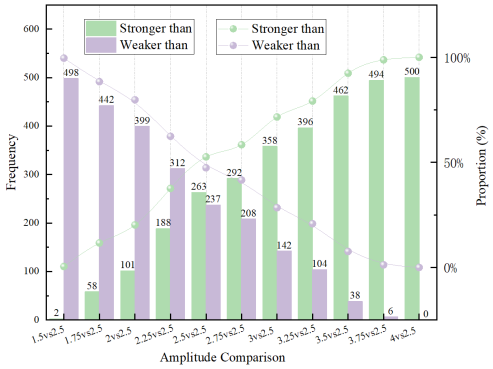

Figure 10. Frequency statistics of comparison results.

The just-noticeable difference (DL) was calculated using Equation (6):

$$DL = \frac{(S_1 - S_t) + (S_t - S_2)}{2}$$

where S_1 denotes the comparison stimulus that was judged stronger than the standard stimulus in 75% of the trials, S_2 denotes the comparison stimulus judged weaker than the standard stimulus in 75% of the trials, and S_t represents the standard stimulus.

Based on the experimental results, a curve-fitting procedure was performed, yielding a difference threshold of $DL = 0.56V$.

It should be noted that the threshold identified in this study is not intended to represent an absolute or differential threshold in the strict psychophysical sense.

Instead, this experiment serves as a preliminary calibration step to determine an appropriate stimulation intensity for subsequent experiments. The goal is to ensure that the vibrotactile stimuli are consistently perceivable across participants, thereby minimizing the risk that perceptual failure is caused by insufficient stimulus intensity rather than the encoding strategy itself.

Direction Recognition Experiment Based on Phantom Tactile Sensation

Objective

Building on the vibrotactile perception threshold results obtained in the previous stage, this experiment aims to further evaluate the feasibility and performance of phantom tactile feedback in directional guidance tasks. Since phantom tactile sensation can generate a continuous virtual tactile point by adjusting the intensity and activation sequence of adjacent vibration actuators, it has the potential to provide higher-resolution directional cues using only a limited number of motors.

In this experiment, participants completed multi-direction recognition tasks to compare different vibrotactile encoding strategies—specifically, single-point phantom guidance and dynamic phantom guidance. By assessing their differences in directional judgment accuracy, feedback continuity, and perceptual clarity, the experiment examines whether phantom tactile sensation can serve as an effective interaction mechanism for wearable guidance systems.

Experimental Design and Stimulation Encoding Modes

Directional guidance was achieved by modulating the intensity ratio between two adjacent vibration motors. Six target directions were rendered under both single-point and dynamic phantom guidance modes: ±45°, ±90°, and ±135°.In the single-point phantom guidance mode, the intensity of the phantom tactile point was fixed at 2.5 V, with each stimulus lasting 3000 ms.

In the dynamic phantom guidance mode, the phantom point always began at 0°, moving clockwise for positive directions and counterclockwise for negative directions, stopping upon reaching the designated target angle. The phantom point moved at a constant speed, following the optimal tactile motion velocity suggested by Ali Israr et al., i.e., 60 mm/s [16].

A custom experimental interface developed in Python was used for the task. The interface consisted of: (1) A dial-based interaction area, allowing participants to intuitively select the perceived direction; (2) A data-recording area, where the selected direction was confirmed and automatically converted into an angle value, which was then logged by the software.

After the experiment began, target directions were randomly generated and rendered to produce the corresponding phantom tactile point. Participants reported the perceived direction using the dial interface with a resolution of 1°. In both phantom tactile encoding modes, each target direction appeared randomly five times, resulting in a total of 60 data entries per participant.

Result Analysis

The results of the single-point phantom guidance experiment are shown in Figure 11. The mean perceived directions for the six target directions were all close to their intended angles, specifically: +48.11°, −48.97°, +87.64°, −94.99°, +127.90°, and −127.71°. The overall mean error across all directions was 9.573°. Each direction exhibited a number of outliers, likely due to perceptual fatigue. In the single-point guidance mode, each target direction is always associated with a fixed motor and a constant vibration frequency. After multiple repetitions, the lack of variation in stimulation may have led to reduced sensitivity or adaptation effects, causing increased directional judgment errors.

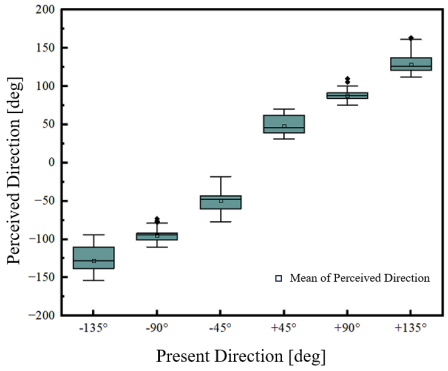

Figure 11. Distribution of single-point phantom sensation direction recognition.

The results of the dynamic phantom guidance experiment are shown in Figure 12. The mean perceived angles for the six target directions were +51.17°, −49.45°, +92.40°, −87.26°, +131.82°, and −130.44°, with an overall mean error of 8.806°. The directional errors in the dynamic phantom condition were smaller than those observed in the single-point phantom condition. From a cognitive perspective, this improvement primarily stems from the differences in stimulation characteristics between the two encoding modes. During the experiment, the dynamic phantom condition generated a smoothly moving tactile trace on the skin by continuously varying the vibration intensity, thereby maintaining temporal continuity in directional cues. Compared with the discrete single-point stimulation, this continuous form of guidance enables participants to construct a coherent spatial mental trajectory, reducing cognitive interruptions and memory load during information decoding.

From a human–computer interaction standpoint, the “motion-continuity cues” provided by dynamic phantom feedback align more closely with the natural mechanisms of human perceptual integration. This facilitates more stable directional perception and enhances spatial localization performance.

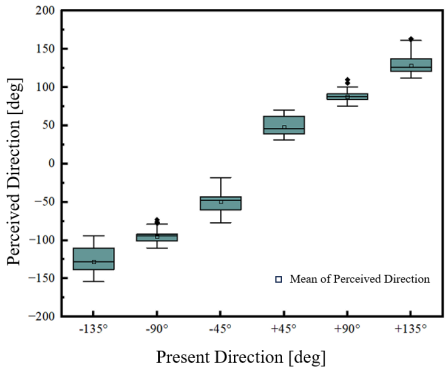

Figure 12. Distribution of dynamic phantom sensation direction recognition.

In addition to the task-based evaluation, a structured subjective assessment was conducted to further examine user experience across the two vibrotactile guidance modes—single-point phantom guidance and dynamic phantom guidance. Participants rated each condition using a 5-point Likert scale in terms of perceived naturalness, continuity, intuitiveness, and cognitive effort.

The results indicate that the dynamic phantom guidance mode received higher ratings in naturalness, continuity, and intuitiveness compared to the single-point phantom guidance mode. In contrast, no significant difference was observed in cognitive effort between the two modes.

The improved ratings in naturalness and continuity may be attributed to the spatiotemporal integration of stimuli across adjacent actuators, which creates a smooth perceptual transition of the virtual tactile point. This continuous sensory experience is more consistent with how humans perceive motion on the skin, thereby enhancing the overall naturalness of the feedback. Similarly, the higher intuitiveness of the dynamic phantom guidance mode may result from the presence of implicit motion cues, which provide users with a more direct and interpretable sense of direction compared to discrete, static stimulation.

It should be noted that this evaluation is based on subjective ratings with a limited sample size and may be subject to individual bias. Future work will incorporate standardized workload assessment methods for more rigorous validation.

DESIGN CASE

Design Objectives and Requirement Analysis

Based on the above research, a wearable phantom tactile guidance wristband integrating directional guidance and safety assistance functions was designed to address travel scenarios such as metro station entry, where environmental noise is significant, auditory channels are easily occupied, and indoor positioning accuracy is limited. The proposed device aims to provide visually impaired users with a more reliable tactile-based guidance approach.

As illustrated in Figure 13, the overall structure of the wristband consists of a vibration module, an IMU module, an RFID module, and control and power supply modules. The IMU module is used to detect changes in the user's orientation, while the RFID module interacts with spatial positioning infrastructure and a BIM system within the metro environment to update the user's location in real time. The control module integrates data from both sources via a microcontroller, computes the relative direction to the target, and drives the vibration module to deliver tactile feedback.



Figure 13. Product structure display and wearing diagram.

Distributed vibration actuators are embedded along the inner band of the wristband, enabling the generation of dynamic phantom tactile trajectories based on directional signals to support directional perception. The system is powered by a lithium battery and adopts a magnetic charging design to achieve a lightweight form factor and extended battery life suitable for wearable use.

Design Objectives and Requirement Analysis

A simulated demonstration was conducted based on a typical metro travel scenario, focusing on how the system guides users through fare gates during station entry. The overall architecture of the guidance system for this scenario is illustrated in Figure 14.

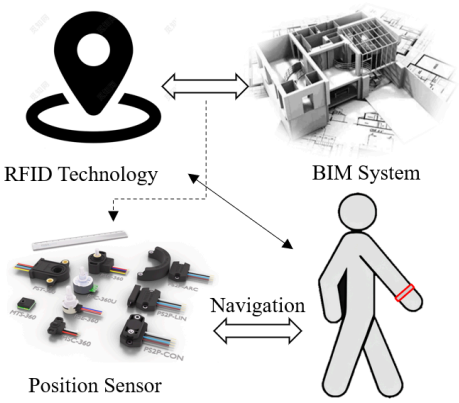

Figure 14. System Architecture of the Guidance System.

The product adopts phantom tactile vibration feedback as its core interaction mechanism and achieves spatial guidance through the coordinated integration of position sensing and orientation recognition. The power module supplies stable electrical energy to all functional units, while the control module—embedded with a

microcontroller—handles data processing and command allocation, serving as the central control unit of the system.

The usage scenario of the product is illustrated in Figure 15. During the guidance process, the wristband interacts with RFID tag nodes deployed within the metro station via the RFID module to obtain the user's real-time location, which is then uploaded to the BIM system. Based on the spatial information, the BIM system determines whether the user has entered the fare-gate area and transmits the coordinates of the target point accordingly. Meanwhile, the built-in IMU module continuously monitors the user's wrist posture and rotational angle to determine the current heading direction. The control module fuses the data acquired from the RFID and IMU modules to calculate the angular deviation between the user's current orientation and the target direction. This deviation is subsequently mapped into tactile signals and rendered as directional vibration feedback. Through perceiving the vibration cues generated by the wristband, users are able to identify the target direction and achieve a safe and continuous guidance experience in the noisy metro entry environment.

In summary, the experimental design follows a logical structure consisting of perceptual capability assessment, parameter extraction, and guidance-mechanism validation. The two experiments are interlinked and collectively form the core basis for constructing the parameter model of the phantom tactile guidance system. The findings provide essential data support and experimental evidence for subsequent wearable-product development and system design.

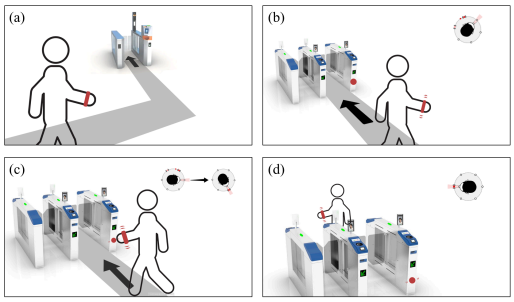

Figure 15. Product usage scenario.

Structural and Material Design

The structural design of the proposed product follows the principles of lightweight construction, flexibility, and wearable comfort. The guidance wristband adopts a circular modular architecture composed of a main

housing, a flexible strap, and embedded electronic units. The main housing integrates the control module and a lithium battery, while multiple linear vibration actuators are distributed along the inner side of the strap to form a closed-loop tactile feedback configuration, enabling the continuous transmission of multidirectional phantom tactile signals. The IMU and RFID modules are positioned on opposite sides of the wristband for orientation sensing and localization communication, respectively. Flexible flat cables are used to interconnect the modules, ensuring signal stability while maintaining structural integrity.

In terms of material selection, the strap is made of high-elastic, skin-friendly silicone as the primary contact material, providing both softness and breathability. This choice helps reduce skin pressure and thermal discomfort during prolonged wear. The main housing adopts a composite structure combining lightweight anodized aluminum and ABS plastic. Overall, the structural and material design balances functional integration with wearing comfort, offering a practical reference for the long-term use of tactile guidance devices across different application scenarios.

CONCLUSIONS

This study proposes a wearable phantom tactile feedback system for directional guidance in complex transportation environments. By leveraging conductive fiber integration, this system ensures stable signal transmission and ergonomic haptic delivery within a lightweight, textile-based interface. The research systematically investigates the perceptibility, encodability, and applicability of phantom tactile feedback for directional guidance. Through absolute and difference threshold experiments, the effective vibration perception range of the wrist area was quantified, providing parameter references for subsequent encoding design. Based on these perceptual findings, two phantom tactile guidance encoding methods—single-point phantom feedback and dynamic phantom feedback—were designed and comparatively evaluated. Experimental results indicate that both methods achieve relatively high directional recognition accuracy, while dynamic phantom feedback demonstrates superior performance in terms of continuity, intuitiveness, and recognition stability. This characteristic makes it particularly suitable for continuous locomotion-oriented guidance scenarios.

Drawing on the experimental outcomes, this study further derives design principles at the levels of interaction mechanisms, feedback encoding strategies, hardware structure, and usage workflows. A conceptual product design was developed and illustrated using a metro entry scenario as an example to demonstrate application feasibility. Future work should focus on optimizing fiber-based structural ergonomics and exploring multimodal integration with visual and auditory cues to enhance applicability and scalability in real-world contexts.

By refining the textile-integrated sensory layout, these systems can achieve superior wearing comfort while maintaining high signal fidelity for complex navigation tasks.

Author Contributions

Conceptualization –Xueqin Li and Weizi Xu; methodology – Xueqin Li and Weizi Xu; investigation – Xueqin Li and Weizi Xu; writing-original draft preparation – Xueqin Li and Weizi Xu. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research received no external funding.

Acknowledgements

Not applicable.

REFERENCES

[1] Wang S. Research on Measurement and Improvement Strategies of Barrier-Free Quality in Travel-Friendly Urban Non-Motorized Spaces. Masters Thesis, North China University of Technology, 2025.

[2] Zhao L, Yang G, Zhou Q, Zhang Y, Qiu Y. A Comparative Study on Accessible Construction of Urban Environment in China and the Selected Countries. Urban Development Studies. 2014; 21: 4-7.

[3] Zhang X, Yao X, Hu F. Embodied Cognition Based Design and Verification of ContinuousTactile Guiding Products for the Visually Impaired. PACKAGING ENGINEERING. 2021; 42: 113-119. doi:10.19554/j.cnki.1001-3563.2021.16.015.

[4] Kim Y, Lee J, Kim G.J. Extending “out of the body” tactile phantom sensations to 2D and applying it to mobile interaction. Personal and Ubiquitous Computing. 2015; 19: 1295-1311. doi:10.1007/s00779-015-0894-4.

[5] Lee J, Kim Y, Kim G. Funneling and saltation effects for tactile interaction with virtual objects. In Proceedings of the Human Factors in Computing Systems, 2012. doi:10.1145/2207676.2208729.

[6] Wang Y, He L, Xiao D. Haptic Interaction Experience in Smart Homes. PACKAGING ENGINEERING. 2022; 43: 37-49+108. doi:10.19554/j.cnki.1001-3563.2022.16.004.

[7] Massalim Y, Kappassov Z, Varol H.A. Deep Vibro-Tactile Perception for Simultaneous Texture Identification, Slip Detection, and Speed Estimation. Sensors. 2020; 20: 4121. doi:10.3390/s20154121.

[8] Ghiani G, Leporini B, Paternò F. Vibrotactile feedback to aid blind users of mobile guides. Journal of Visual Languages and Computing. 2009; 20: 305-317. doi:10.1016/j.jvlc.2009.07.004.

[9] German F, Sri K, Roberto M, Eric M, M M.L., Akin S.E. Vibrotactile Guidance for Wayfinding of Blind Walkers. IEEE transactions on haptics. 2015; 8: 306-317. doi:10.1109/toh.2015.2409980.

[10] See A.R., Costillas L.V.M., Advincula W.D.C., Bugtai N.T. Haptic Feedback to Detect Obstacles in Multiple Regions for Visually Impaired and Blind People. Sensors & Materials. 2021; 33. doi:10.18494/SAM.2021.3221.

[11] Li L, Wu J, Song A. Driectional cueing experiments of wearable Vibrotactile belt. JOURNAL OF SOUTHEAST UNIERSITY (Natural Science Edition). 2009; 39: 82-86.

[12] Békésy G.v. Funneling in the Nervous System and its Role in Loudness and Sensation Intensity on the Skin. The Journal of the Acoustical Society of America. 2005; 30: 399. doi:10.1121/1.1909626.

[13] David A. Information Transmission by Phantom Sensations. IEEE Transactions on Man Machine Systems. 1970; 11: 85-91. doi:10.1109/tmms.1970.299967.

[14] Jose S, Keisuke O, Yasuhisa H. Path-Following Guidance Using Phantom Sensation Based Vibrotactile Cues Around the Wrist. IEEE Robotics and Automation Letters. 2018; 3: 2485-2492. doi:10.1109/lra.2018.2810939.

[15] Schafer N, Seiler J, Latsch B, Kupnik M, Beckerle P. Vibrotactile Phantom Sensations in Haptic Wrist Rotation Guidance. IEEE transactions on haptics. 2025; PP. doi:10.1109/toh.2025.3542604.

[16] Israr A, Poupyrev I. Tactile brush: drawing on skin with a tactile grid display. In Proceedings of the Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, 2011; pp. 2019-2028. doi:10.1145/1978942.1979235.

[17] Ge S, Lin Y, Lai S, Xu J, He Y, Zhao Q, Zhang H, Xu S. A Virtual Vision Navigation System for The Blind Using WearableTouch-vision Devices. Progress in Biochemistry and Biophysics. 2022; 49: 1543-1554. doi:10.16476/j.pibb.2021.0320.

[18] Du J. Design and Application of Vibration Tactile Coding. MASTER THESIS, UNIVERSITY OF ELECTRONIC SCIENCE AND TECHNOLOGY OF CHINA, 2021.