Supplementary Information for

Tactile Perception Evaluation Interactive System Based on Electrotactile Virtual Reality

This PDF file includes:

Supplementary Notes 1

Captions for Supplementary Videos 1

Supplementary Figure 1 to 9

Supplementary Tables 1 to 2

Other Supplementary Materials for this manuscript include the following:

Supplementary Videos 1

Supplementary Note 1 | Experimental paradigm for electrotactile data acquisition in 30 participants.

I. Experiments with human subjects. The experiments with human subjects were performed in compliance with all the ethical regulations under a protocol that was approved by Zhujiang Hospital of Southern Medical University. A total of 30 volunteers participated in this experiment. All of the volunteers gave written informed consent about the experimental procedure. All participants were trained to manipulate the electrotactile system with the help of experimenters until they understood the sensation of electrical stimulation.

II. Body Composition Data Collection. Participants initially measure their body composition using a body fat scale. A body fat report is printed for each participant for record-keeping purposes. It is important to note that these reports are confidential and must not be disclosed or discussed in public settings.

III. Perception and Pain Threshold Test. Testing begins with a current amplitude of 0.05mA, incrementally increased to find the perception threshold. The process continues with gradual increases in current until the pain threshold is determined. For subsequent tests, the experimental current is set at half the sum of the perception and pain thresholds.

IV. Testing with and without Inhibitory Electrodes.

Comparative Experiment Setup:

Pre-experiment Preparation: Participants initially experience microcurrent stimulation corresponding to simple line graphics (horizontal, vertical, left diagonal, right diagonal) twice each. This helps participants familiarize themselves with the experimental process and the sensory stimulation.

With Inhibitory Electrodes Test: Participants test five different graphic arrangements using the four basic shapes. After receiving the corresponding microcurrent stimulus for each pattern, participants report the perceived graphic, and the system records the reaction time for perception. The arrangements, as shown in Table 1, are tested sequentially, row by row, by the participants.

Without Inhibitory Electrodes Test. Participants repeat the same graphic arrangements to evaluate the differences in stimulation effects when inhibitory electrodes are absent. This part of the experiment aims to compare the clarity and intensity of tactile feedback with and without the use of inhibitory electrodes.

V. Testing Experiment with 10 Pattern Types.

Pre-experiment Preparation: Participants experience microcurrent stimulation for 10 different patterns, with each pattern experienced twice. The patterns are categorized into three types: Simple lines (horizontal, vertical, left diagonal, right diagonal), Geometric shapes (cross, X-shape, square, rectangle), and Complex figures (smiley face, sad face).

Experiment Procedure: At the start of the experiment, participants proceed according to the sequence outlined in Table 2. The test involves five patterns per group, with each pair of opposing patterns sequentially numbered from 1 to 10 in Table 2 for the perception tests. Participants are required to choose between two options to identify the pattern they perceive. The sequence and organization in Table 1 facilitate systematic testing and structured response collection, ensuring each participant's response aligns with the standardized experiment design.

Table 1. Test Sequence for Simple Line Graphic Perception

<table>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><td rowspan="5">simple line</td><td>—</td><td>|</td><td>/</td><td>\</td></tr>
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Table 2. Pattern Perception Identification Test Sequence

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
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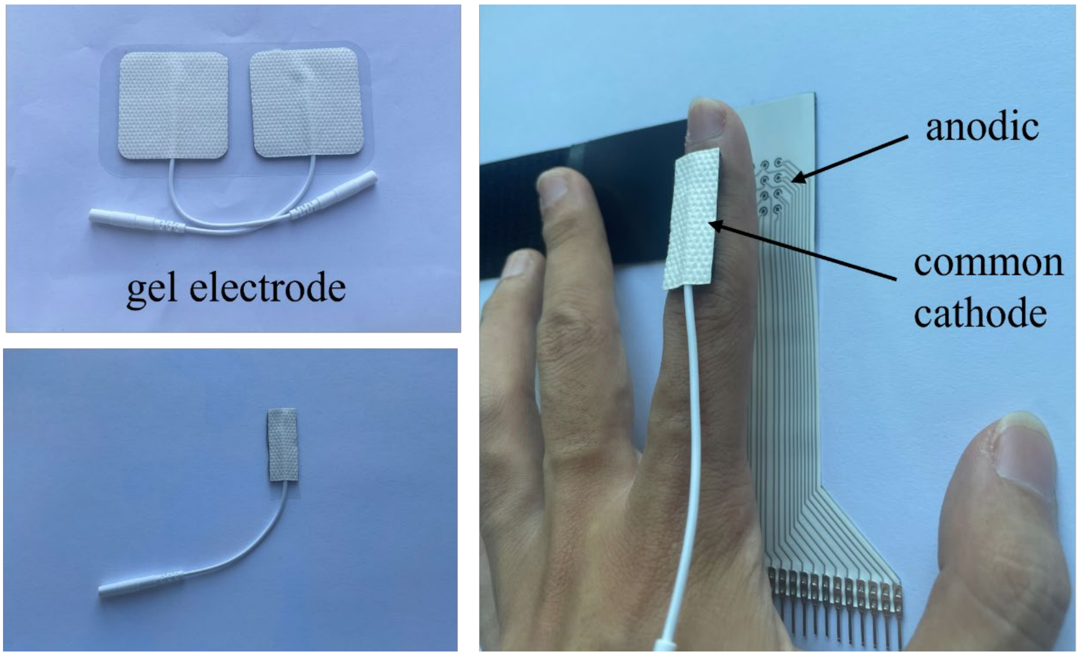
Supplementary Video 1 |

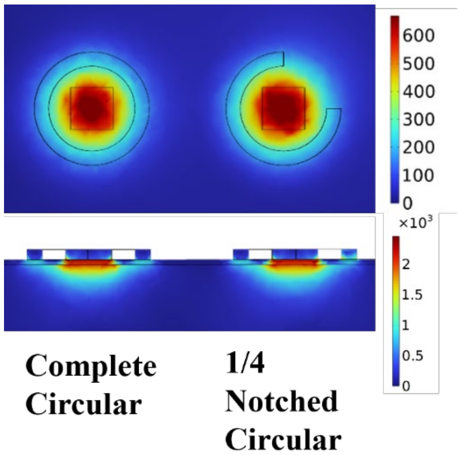
In this demo, we show the Tactile Perception Evaluation Interactive System (TPEIS) built on Unity for quantitative evaluation of tactile perception ability in a virtual environment. The system scene is set in a virtual space station, where subjects perceive virtual haptics by touching virtual patterned dots, thus enhancing the fun and immersion of the assessment. At the beginning of the demonstration, a threshold selection interface was shown, where subjects could select the appropriate microcurrent level (1mA, 2mA or 4mA) before the experiment. Subjects wore a VR headset and touched the buttons with their virtual hands to experience the stimulation of different current gears, so that they could choose the most comfortable threshold setting for subsequent experiments. Next, the pre-experimentation phase was demonstrated, in which subjects familiarised themselves with the sensation of tactile perception by experiencing different patterns of microcurrent stimulation. In this phase, a virtual finger generated by the Ultraleap 3Di technology in the VR glasses touched a pattern on the screen, which changed to a lightning symbol when touched, signalling the onset of the microcurrent stimulation. In the pattern recognition task, subjects clicked on an unknown question mark pattern in a virtual box and judged its corresponding pattern type by tactile perception, and the system recorded the result and reaction time of each judgement to further quantify the tactile perception ability. Finally, a tactile perception evaluation report is shown, which is generated based on the subject's judgement results, including the tactile perception score, and provides corresponding suggestions based on the score. If the score is below the lower limit of the standard deviation, the system will suggest to improve the tactile perception ability through repetitive electrical stimulation training.

Supplementary Fig. 1 | Model 3800 MultiStim: 8-Channel Stimulator. The Model 3800 MultiStim is a high-performance electrophysiological device primarily used in the medical field for electrophysiological research and treatment. It is capable of providing various stimulation modes, including single pulse, dual pulse, and continuous stimulation, and offers adjustable parameters such as frequency and amplitude. The generator has four isolators for converting the pulsed signal into the required stimulus and suppression currents. This versatile device is widely used in fields such as neuromuscular electrophysiological examinations, rehabilitation therapy, and acupuncture. Its features make it highly suitable for electro-tactile feedback applications.

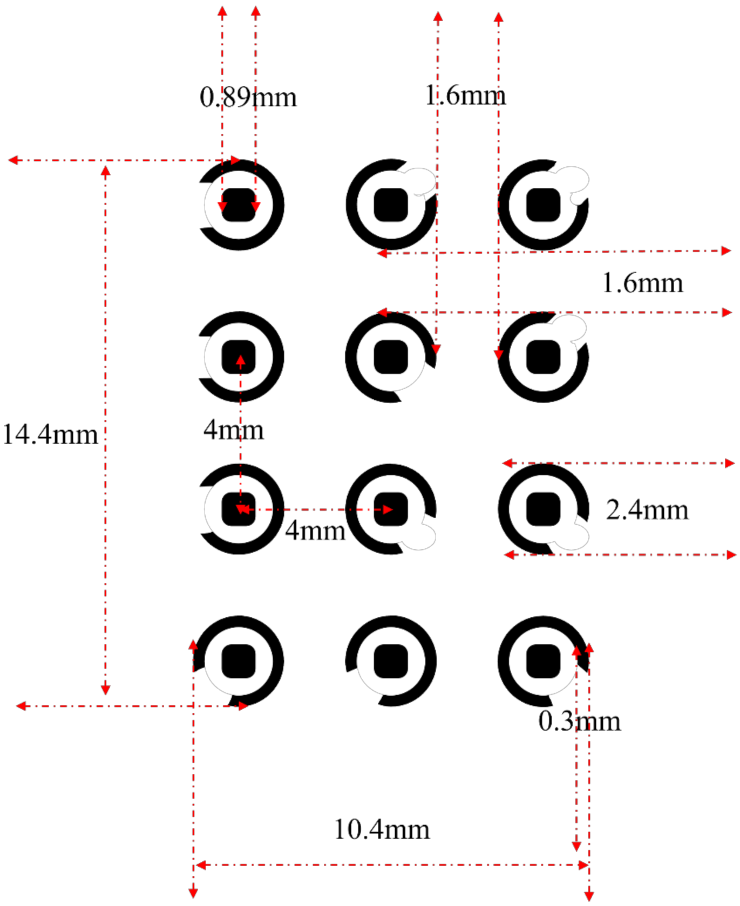


Supplementary Fig. 2 | Optical image schematic of the fingertip-grounding electrode. The gel electrode is from Shenzhen Baijianda Technology Development Co., Ltd., with product model BJD-B.

Supplementary Fig. 3 | Surround-Inhibitory Electrode Structure. The outer ring electrode serves as the inhibitory electrode, while the central square electrode functions as the stimulating electrode.

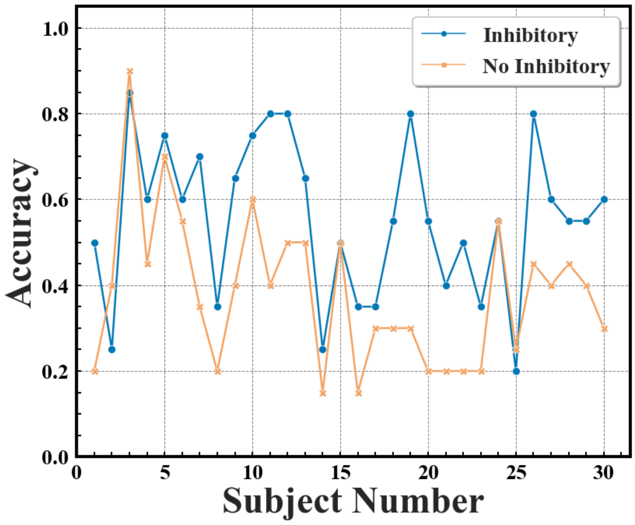


Supplementary Fig. 4 | Simulation results of current density distribution with and without a 1/4 gap in the ring-shaped electrode.

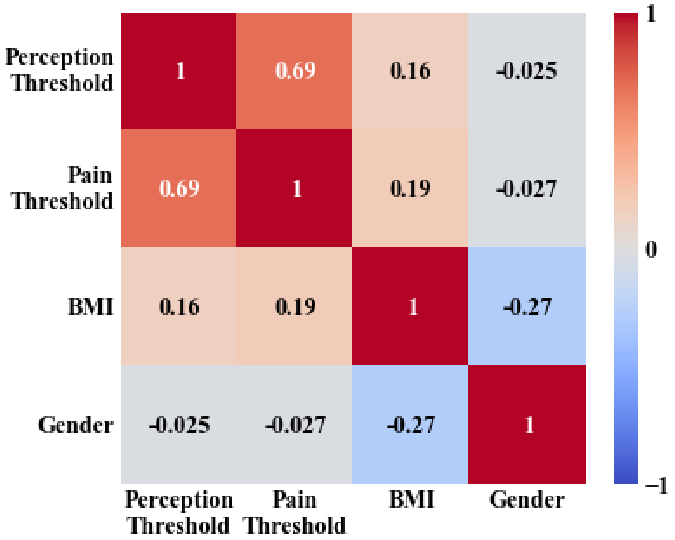


Supplementary Fig. 5 | Dimensions and Spacing of the Electrode Array. The electrode array consists of 12 electrodes with a surrounding inhibitory structure. Each surrounding inhibitory electrode is designed as a ring with a diameter of 2.4 mm, where the width of the inhibitory electrode ring is 0.3 mm, and the central stimulating electrode is a square structure with a side length of 0.89 mm. The spacing between the surrounding inhibitory electrodes is 1.6 mm, while the distance between the centers of two stimulating electrodes is 4 mm, which aligns with the typical two-point tactile threshold range for human fingertips (2-4 mm). The total size of the electrode array is 14.4 mm × 10.4 mm, which sufficiently covers the average tactile sensitive area of the general population (approximately 1-1.5 cm^2).

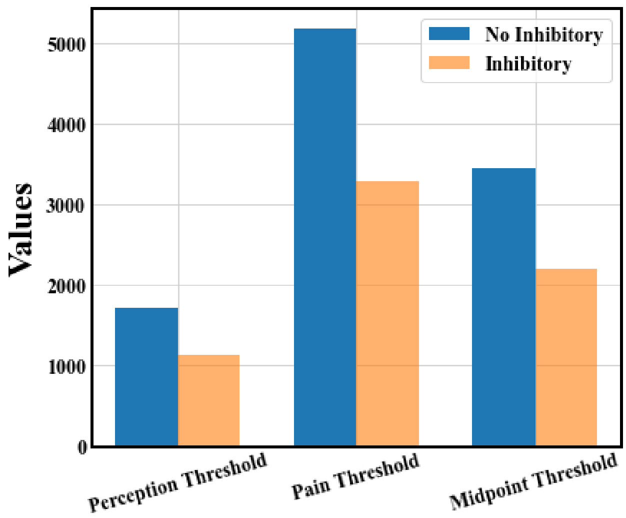
Supplementary Fig. 6 | Physical Image of the Multi-channel Gate Electrode for Temporal Gating. The multi-channel gate electrode, which controls the activation of electrodes, is controlled by STM32. By sending control information to the STM32 via Bluetooth, virtual tactile pattern stimuli can be generated on the electrode array. The gating circuit is based on a microcontroller (MCU) that controls the 74HC595 shift register via an SPI interface to achieve multi-channel expansion and selection functionality. By incorporating the ULN2803 Darlington array, the output driving capability of the chip is enhanced, enabling precise control of the electrode array through solid-state relays. The system is designed with modularity, using multiple cascaded 74HC595 modules to expand the number of channels. The output signals from the 74HC595 are amplified by the ULN2803 and used to drive the solid-state relays, which control the switching of the electrode array, thus completing the transmission of the selection signal. This design features high scalability, strong driving capability, and high reliability, with the standard header interface allowing for convenient expansion and connection of the electrode array. The overall design ensures the stability and accuracy of the microcurrent tactile feedback system, providing robust hardware support for virtual tactile experiences.



Supplementary Fig. 7 | Comparative line plots of recognition accuracy of each of the 30 participants for simple line patterns with and without inhibitory electrodes.



Supplementary Fig. 8 | Correlation confusion matrix analysis of perception threshold, pain threshold, BMI, and gender.



Supplementary Fig. 9 | Comparative analysis of thresholds with and without inhibitory electrodes.