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E-Pad: A Comfortable Electrocutaneous-based Tactile Feedback Display

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ABSTRACT

The devices with touchscreen are becoming more popular recently; however, most of them suffer from the crucial drawbacks of lacking accurate tactile feedback. A novel electrocutaneous-based tactile device with the name of E-pad is proposed to provide a dynamic and static low-voltage feedback for touchscreen. We optimize the key parameters of the output voltage and design custom-made hardwares to guarantee a comfortable user experience. Users could move their fingers freely across the touchscreen of the proposed device to really feel virtual objects. Two preliminary experiments are conducted to evaluate the interactive performance of the proposed device and the experimental results show that the proposed device can provide a comfortable and distinct tactile feedback.

1. INTRODUCTION

A major problem with the touch interface is the lack of intense and precise tactile feedback. Without the haptic feedback, the touch interface decreases the realism of visual environments and reduces the efficiency of the interface.[1] Thereby more and more haptic devices for touch-based interactive systems have been proposed, which can provide tactile feedbacks to a user on the touch surface.[2,3]

Various solutions aiming at providing tactile feedback with touchscreen for bare fingers have been proposed such as vibration,[5] piezo,[4] gesture output ,[9] ultrasonic[6,10] and electrovibration .[11,12,29]Besides, methods about multiple modalities like vibro-electro-tactile have been used by some researches, to get more afferent streams for fingers.[7] Although certain solutions for touchscreen can provide efficient tactile feedbacks under the controlled environment, there are few solutions of developing an interface with intense and high-speed tactile feedback for both static and dynamic fingers.These years, researches about how electrocutaneous stimulation produces the tactile sensations on skin were studied and tested.[8] Electrocutaneous sensation is based on current stimulation, i.e. the tactile feedback increases with current density, which means that a wide range of intense tactile sensations can be created in a short time. Another advantage of electrocutaneous is that energy efficiency is only relative to the contact parameters between users and the screen, and this ensures that electrocutaneous can be utilized in any size of screen. Kijimoto proposed the Skeletouch [13] with multi-electrode arrays. However, such device is driven by a high-voltage source (350V) with current-controlled, which fails to provide a comfortable user's experience. Meanwhile this technique require static fingers when feeding back haptic texture.

To solve such problems, a novel device as shown in Fig. 1 was proposed in this paper. We not only lowered the output voltage to under 60V and adopt positive and negative polarity, but also made a special hardware to guarantee comfortable user experiences. When an image is displayed on the touch surface, the proposed E-Pad provides an immersive way of feeling the virtual objects both for static and dynamic fingers. The resolution of the output tactile feedback is less than 2mm, which is dependent on the resolution of finger tracker. Two preliminary evaluations were also performed, and the results showed that E-Pad could provide distinct and comfortable tactile feedback with low voltage.

Furthermore, we evaluated the electrostimulation technique with a customized steering law, and we compared it with the vibration technique to study the effect of tactile feedback.

In this paper, our work has the following two contributions:

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Figure 1. The tactile device which includes a mobile computer, an electrocutanous surface and a custom-made haptic driver

- We developed a feedback platform to achieve low-voltage electrical stimulation tactile feedback, and verified the feasibility of electrocutaneous feedback;
- We evaluated the electrocutaneous tactile technique by steering task based on Fitts' Law, which proved that the deficiency of the prior could be compensated by the electric stimulation technique.

2. SYSTEM DESIGN

The design of E-Pad focuses on reinforcing feedback and comfort of tactile display on the touchscreen without significantly increasing its cost and complexity. The most relevant issue is the safe implementation of the system since an improper current may hurt the cells and organs of its user.

2.1 Mechanism

The perceived strength is relative to the input energy consisting of current, voltage and pulse width ,[15,16] contact size, material, contact force, skin location, thickness and hydration .[17–20] Thus voltage, pulse width and screen material are chosen as the parameters to regulate the stimulation for fingers on the touch screen. Another useful dynamic intensity range of an electrocutaneous stimulator is P/S ratio ((threshold of pain)/(threshold of sensation)) which varies from under 2 (6dB) to about 10 (20dB),[21] and it is a function of electrode size, material and waveform.

The P/S ratio increases with the electrode size .[21] The contact size between the single finger and the touchscreen is smaller than $200mm^2$. Larger contact size will occasionally drop the resistance of one's skin,[22] which may result in that the current density increases sharply and a sudden sharp sting on the skin. Therefore, a real-time feedback circuit is designed to measure the contact size through the electrical impedance, and the voltage will decrease when the resistance suddenly falls. For pulse durations longer than 500s, the pain threshold drops more quickly than the sensation threshold and the period of the waveform is limited accordingly.

A comfortable feedback using impedance was designed to protect the user. Firstly, the maximum of output current was 5 mA under which nerve damage can't be caused by long-term exposure .[23,24] Secondly, long-term nerve damage can be avoided by using biphasic, charge-balanced pulses [25] which have an initial phase of positive polarity and a second phase of negative polarity. The charge delivered by the first phase was equal and opposite to what was delivered by the second phase. At last, the output pulse was connected with the inductance before the electrode to prevent the sharp increasing of the instantaneous current.

2.2 Definition of E-Pad System

The E-Pad can extract the texture data from the display image and provide tactile feedback to the fingers. Fig. 2 shows the system diagram. The proposed device was divided into two parts: a control unit in which tactile stimulations were generated and regulated, and a display unit that displayed the images and sent the rendering data of image texture to the control unit. The display unit consist of a mobile computer and an infrared touch screen composeing of a transparent electrode sheet(ITO) applied onto a glass substrate. An infrared touch frame whose spatial resolution was 2mm attached

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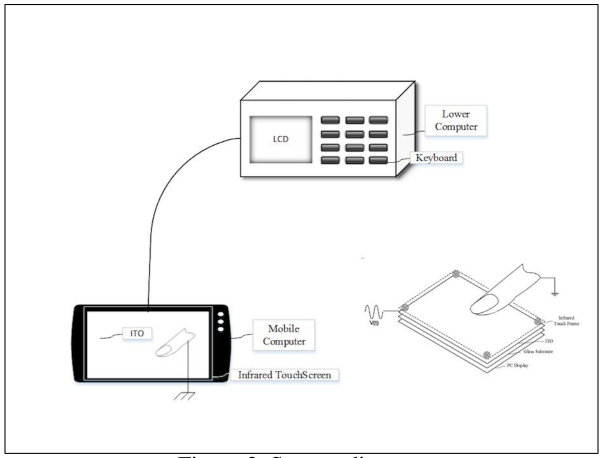

Figure 2. System diagram

on the glass, which also limited the resolution of tactile output. The control unit consist of a lower computer, keyboard and LCD display.

When the E-Pad is booted up, user could choose the image displayed on screen, then the display unit drives the PC display to show the corresponding image on the screen and begins to gather data of finger position via infrared touch frame. The relevant rendering data of tactile information will be sent to the control unit when the user's finger touches the screen. The electrocutaneous stimulation is produced by the control unit according to the rendering data and fed back to the finger.

2.3 Hardware

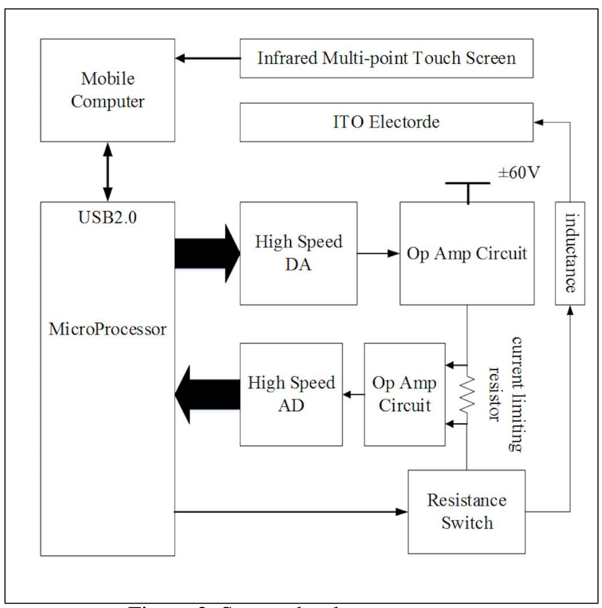

Figure 3. System hardware structure

Fig. 3 illustrates the system hardware structure. The update rate of the control loop was less than 10 μs. The system used a high-speed microprocessor (PIC 33) as the main controller, and also included a high speed DA converter, a high speed AD converter and two analog OP amp circuits. The electrocutaneous stimulation was generated by the microprocessor according to the rendering data from mobile PC, and then it was turned into analog pulse by the DA converter. The simulation pulses were magnified from -5 –+5V to -60V–+60V by an OP amp circuit, and the pulses passed through a resistor which limited the max output current and monitors the change of output current. The stimulation pulse went through the resistance switch that changes the resistor value according to the command from microprocessor.

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The resistance switch was a custom-made circuit which includes 16 values of output resistance. The output current was limited by the output voltage and the resistance switch that can change the tactile sensation. The pulse was regulated by the inductance to prevent the sharp increase of current before the pulse was connected to the ITO electrode. The P/S ratio increased obviously in a separate experiment when the inductance was added to the circuit.

2.4 Comfortable feedback

It was necesseary to consider the characteristic of user's skin when the system real-time rendered the texture information of the image. We regulated the output voltage by changing the value of resistance switch in accordance with the change of human skin to prevent the sudden stabbing caused by temporal high current density. When the finger touched the screen, the output current suddenly changed and the voltage on the current limiting resistor responed to the change of current. However, the voltage was too small to be processed immediately, so the voltage signal was amplified through OP amp circuit and the voltage data were captured by AD converter. Then the microprocessor received the data and changed the output voltage according to the feedback voltage. There were three circumstances that the microprocessor will change the output voltage in realtime:

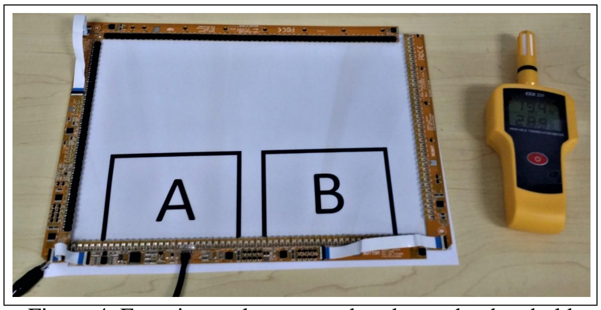

Figure 4. Experimental setup used to detect the threshold

- 1. The resistance switch outputed max value before the finger touches the screen, the voltage and the output resistance changed in realtime according to the rendering data from display unit and the voltage on the current limiting resistor when finger connects with ITO transparent electrode.
- 2. The resistance switch decreased the output resistance by microprocessor when the connecting area was larger than 200mm2, which meant that more than one fingertip touches the screen.
- 3. The output voltage changed immediately when the resistance value of finger decreased unexpected steeply.

3. USER STUDY

We conducted two experiments to evaluate the interactive performance of E-PAD. In the first experiment, we tried to find out whether user can recongnize electrocutaneous tactile information when the voltage of electrocutaneous is less than 60V. The second experiment compared the interaction effect between electrocutaneous technique and vibration.

3.1 EXPERIMENT 1

The E-Pad provided tactile feedback that couldn't be normally experienced in everyday life, thus user study was conducted to understand how users perceives the tactile sensations produced by E-Pad. The fixed waveforms and pulse frequents were chosen to obtain the sensation threshold.

3.1.1 Design

Five adult participants who were recruited by personal invitation participate in the initial experiment. All of the students whose ages were between 20 and 27(sd=2.59) are from Beijing Institute of Technology. Participants were asked to use the index finger of their right hands to scan the touchscreen that was fixed on the table in front of them. Room temperature was 19°C–25°C, and the relative humidity is 20% –40%. The participants washed their hands with soap and water before the experiment, and the fingertip was thoroughly wiped with isopropyl alcohol to remove the skin secretions before each experimental trial. The process of the experiment was as follows:

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- a) Sine wave was picked to estimate the absolute sensation threshold of E-Pad, the output frequency was fixed at 100Hz as well as fixed output resistance. The participants' sensation thresholds were obtained by using a two-alternative forced-choice paradigm.[26] The touch screen was split into two areas marked as A and B as shown in Fig. 4, and the stimulus was randomly assigned to one of them, then the participants were told to find out which area had the signals without moving the finger.
- b) An evaluation experiment was preformed with staircase tracking algorithm. Experiment started with the stimulus voltage much lower than the anticipated threshold. At first, the voltage amplitude was increased by 5V when the participant did an incorrect response from two trials. When the participant made two correct responses, the voltage amplitude was reduced by 5V. After four reversals, the step size of the voltage changed from 5V to 2.5V, and the experiment continued until the amplitude varies by no more than 10V for 8 consecutive trials. Each participant repeated the above test for 4 times and the data of the first time was abandoned.

3.1.2 Result

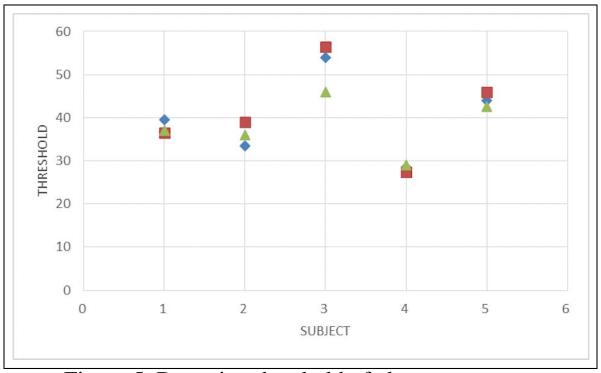

Figure 5. Detection threshold of electrocutaneous

The absolute detection threshold of five participants were shown in Fig. 5. The horizontal axis was the participant number and the vertical axis was the voltage threshold of their perception to the feedback. The absolute mean of the sensation threshold was 39.7±8.4V. The result revealed that users can perceive the tacitle signal of electrocutaneous under 60V and there were distinctions between different participants' threshold(F=27.43, $p < 0.01$), which meant that the output should be regulated according to the corresponding characteristics of different users. Some participants described the tactile feedback as the vibration when their fingers didn't move on the screen. In a separate experiment, one participant reported qualitative difference between sine wave and square wave. The detection threshold levels provided important guidelines for designing tactile interfaces using electrocutaneous.

3.2 EXPERIMENT 2

In order to test the interaction effects of electrical stimulation, we designed a new experiment and evaluated the interactive effect. Experiments were conducted to compare the electrical stimulation with the vibration as a typical feedback technique by designing a special steering task.

For the purpose of fair experiment condition, a preliminary experiment was proposed to adjust the intensity parameters. Ensuring the experiments were completed under the same intensity, the specific output parameters was determined by an informal experiment, which guaranteed the approximation.

3.2.1 Design

This paper investigated the enhancement of the tactile bandwidth of the electrocutanoeous tactile technique and compared with the conventional vibration technique to obtain the reinforcing effect of the user's interactive experience. In order to record the whole process of operation, we took the first contaction with the screen as the start point of timing after the finger pressed the "start" key, i.e. the time was recorded when the icon was selected by participant. For the sake of giving the full play to tactile feedback, the device provided the maximum output feedback force when the user's finger was out of

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the steering. When we were finishing the final operation movement, we calculated the feedback using the distance between the finger position and the center of the End-point. The intensity decreased exponentially. When the finger position was within the area of the target icon, which mean the completion of the icon placement, the system provided multiple short strong feedback to aware the users that the task had been completed.

In the experiment, the independent variables included two feedback techniques, three kinds of tunnel length, four kinds of tunnel width on the screen, and each trail is repeated three times with twelve participants. The total trails of the experiments is:

$$\begin{aligned} &12 participants \times \\ &2 feedbacktechniques \times \\ &3 tunnellength \times \\ &4 tunnelwidth \times \\ &3 repetitions \\ &= 864 trials \end{aligned}$$

We make the following hypothesis: 1) Electrocutaneous feedback technique can reduce the task time; 2) Electrocutaneous feedback technique can effectively improve the accuracy compared with vibration technique;

3.2.2 Task

In this experiment, a task was designed to evaluate the effect of eletrocutaneous tactile. This task needed to meet the following conditions: it could reflect the touch screen-based finger interaction process, which included three basic interaction tasks click, drag and slide; related parameters of the interactive effects could be analyzed via statistics methods. In this paper, we chose and improved the mature circular steering task. There were two kinds of traditional steering tasks. In general, straight steering represents linear movement and circular steering represents non-liner movement. We selected the circular steering task which is more complex than the linear movement task and similar with real interaction for touch screen.

The movement amplitude A was equal to ($2\pi - \theta$) R, the R was the radius. According to the steering law developed by accot and zhai,[27] the Movement Time(MT)could be expressed as the formula: MT = a + bID, where a and b were empirically determined as constants. (see Fig.6.)

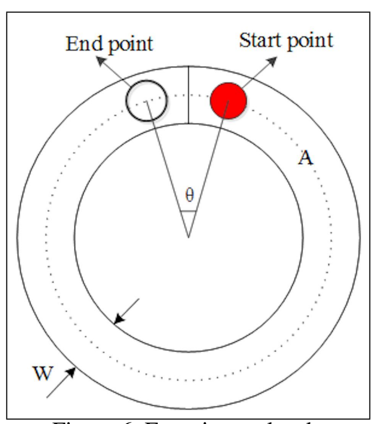

Figure 6. Experimental task

3.2.3 Participants

Twelve paid participants volunteered for the study. 8 were female, and 4 were male. Average age was 26 years (sd = 3.56). All participants were right-handed and had used an interactive tabletop, Apple iPhone, or other similar devices. All of them were recruited from the KUT and BIT university, but nobody was computer scientists or user interface designers. All participants chose to take part in all sessions.

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3.2.4 Procedure

After participants were briefed on the study, they completed a short warm-up session. Participants then began the main experiment consisting of two blocks of trials. The platform could provide elecrocutaneous and Vibration feedback. Participants preformed steering task: circular steering task with enhancing dynamic feedback. At the begin of task, the path to be steered was presented on the touch screen. Participants need to select the icon and then drag the icon passing through the tunnel. After the icon arrived at the precise position, the system would tip the participant that this experiment was already finished and recorded the data of MT(Movement Time), OPM (out of Path Movement) and SD(Standard Deviation). Participants kept doing next trial experiment until the system show Finish experiment. If the participants released the finger from screen before arrive at the precise position, the experiment would be performed again.Participants were asked to minimize errors and move their fingers as soon as possible. For the safety, participants were instructed to use their right index finger to finish the steering task. Finally linear tunnels were to be steered clockwise.

3.2.5 Results

Out of Path Movement(OPM) the electrocutaneous condition achived 7.71% in the overall mean of OPM, while the vibration condition was 11.44%. A one-way ANOVA was profomed to compare the effects of two feedback types(Electrocutaneous and Vibration)

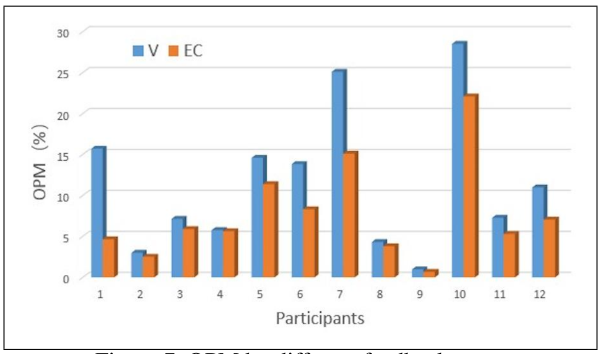

Figure 7. OPM by different feedback types

The ANOVA showed that feedback type had a significant main effect(F(1,23)=11.62,p=0.006), as shown in Fig. 7.It can be seen that participants proformed the task significantly more accurate on electrocutaneous feedback than on vibration feedback. The OPMs are 3.70% lower with electrocutaneous feedback on average than vibration. The ANOVA comparing the effects between different participants showed that there was main effect for participants (F=14.1,p<0.001) Due to the large differences of OPMs among different users, the formula eqref e1 was used to calculate the ratio of personal accuracy improvement. The resulat was shown in Fig.8, and the mean of improved accuracy from OPM was 28%.

$$Z = (OPM(V) - OPM(EC))/OPM(V)\% \tag{1}$$

The results showed that the electro-tactile feedback can improve the accuracy of the touch-screen basic operation such as click and slide, etc.. On the side, the different users had obvious distinction in the sensitivity of the electrical tactile sensation. By comparing the vibration feedback technique, the experiment data showed the electrical stimulation was an effective high-precision tactile technique, which can significantly decrease the OPM. (This confirmed the result of Eve Hoggan et al.[28])

Standard Deviation(SD) The SD data for Experiment 2 was shown in Fig.9. The SD of electrocutaneous condition was,on average, 15.94, comparing to 17.73 of the vibration condition.

A significant main effect for SD was found(F(1,23)=12.95,p=0.004)which meant that participants do the task more reasonable on electrocutaneous feedback than on vibration feedback. The SD of electrocutaneous was 2.67 lower than vibration.

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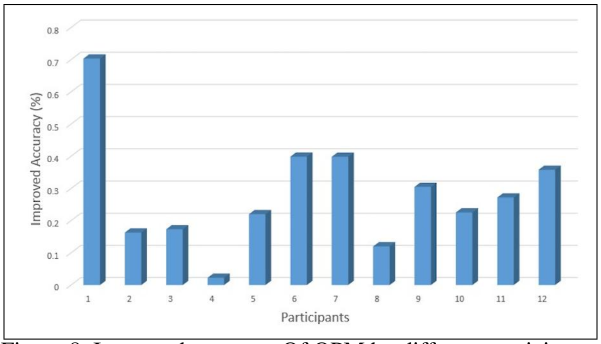

Figure 8. Improved accuracy Of OPM by different participants

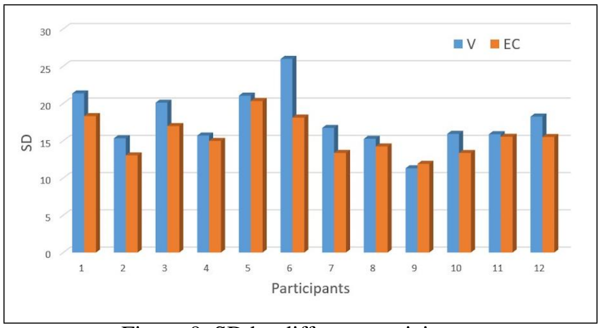

Figure 9. SD by different participants

Comparing to vibration techniques, the results of SD showed that electrocutaneous tactile could effectively decrease the displacement during the mission execution. At the same time, the differences in SD were not as obvious as in OPM. The preliminary study found the correlation with the fat finger phenomenon, which provided data for the further study of steering law with fat finger problem.

Movement Time(MT) An one-way ANOVA test showed that there was no significant effect($F(1,23)=2.96$, $p=0.113$) between different feedback type on MT(see Fig.10). The participants proformed the task no significantly faster on electrocutaneous feedback than on vibration feedback.

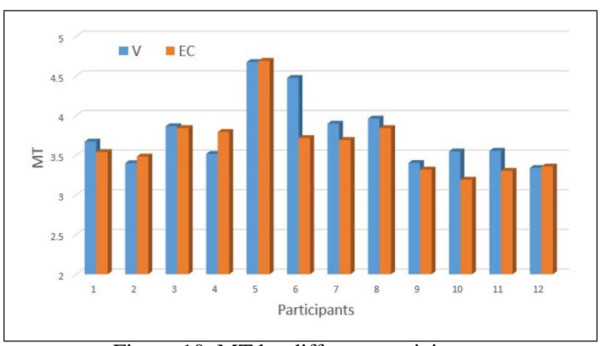

Figure 10. MT by different participants

The experimental results denied the hypothesis that the high precision feedback could reduce the execution time of the task. This verified the experimental results of Minghui sun et al.[29] However, the preliminary study showed that the F value increased gradually as the tunnel length A is longer. It indicated that under the influence of the fat finger effect, the steering law needs to be further studied.

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4. CONCLUSION

A novel technique for touchscreen based on electrocutaneous with the name of E-Pad was proposed in this paper, which could track the finger position and provide intense and comfortable tactile feedback without limitation to finger motion. Two evaluation experiments were conducted to further study the user's perception of E-Pad and provided a foundation for user's interactive performance. The experimental results revealed that the proposed E-Pad provided a more immersive experience of virtual environment and possessed great application potentials in entertainment industry such as games with exciting tactile feedback. Our future study will involve data collection from a broad range of ages whose skin impedance is different and focusing on increasing the P/S ratio that can improve the user's touch experiences.

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