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Combining Suction and Electrotactile Stimulation for a Stable Touch Sensation

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概要: Compact haptic devices hold many potentials to enhance how we interact with virtual environments. For that purpose, this study combined the high spatial and temporal resolution of electrotactile stimulation and the stable pressure sensation of suction pressure. Results showed better realism and strength scores for the combined stimulation with decreased discomfort, suggesting that the proposed system can present enhanced contact sensation with minimal discomfort.
キーワード： 触覚、電気刺激、吸引圧

1. Introduction

Haptic sensations such as those that stimulate the skin and provide extra feedback in Virtual Reality (VR) and Augmented Reality (AR) can better immerse users with their virtual elements. Outside of just VR and AR, haptics may also increase interactivity and convey more types of information to the users.

This study will focus on the implementation of compact haptic devices. Existing methods include the use of electrotactile stimulation [1] [2] [3] and suction pressure sensation [4] [5].

Electrotactile stimulation involves the induction of electrical current onto the skin to stimulate the sensory nerves and is excellent for its spatial and temporal resolution, being able to easily control where each part is stimulated [6] at almost instantaneous speeds that are good for simulating impact sensation. It also only uses low power consumption and hardly needs any space at all and is hence applicable to all sorts of devices such as the sides of smartphones [3]. Its downsides however are that it is uncomfortable for long periods of use and it is also poor at presenting prolonged pressure sensation.

Suction pressure involves suction stimulus to produce a pressure sensation by deforming the skin and is excellent at producing prolonged pressure sensation. This sensation may also sometimes be perceived as a pressed pressure sensation instead of suction [7]. Its downside is that it has low temporal resolution, and hence cannot easily communicate impact sensation. While spatial resolution is possible while still being easily wearable, it can easily make the rest of the system huge and loud due to requiring a larger pump [5].

This study aims to combine electrotactile stimulation and suction pressure sensation to present a more realistic contact sensation within a compact area. The idea is to incorporate electrotactile stimulation in order to provide a better impact sensation and also present detailed areas of contact while having the prolonged pressure sensation handled by suction pressure and reducing the active period of electrotactile stimulation and hence reducing discomfort.

2. System Specifications

2.1 Hardware

Fig. 1 Shows the hardware setup of the suction pressure and electrotactile stimulation device and the ideal way to mount it onto the user's finger which is by holding it. For both parts, an ESP32 microcontroller was used to communicate with a computer with the Windows 10 Operating System via USB.

The suction pressure head was made using an optical 3D printer (Form3, FormLabs) and used Elastic Resin as the material. The pressure inside the suction pressure head is controlled by an electric valve (SC0526GF, SKOOCOM), vacuum pump (SC3701PML, SKOOCOM), and air pressure sensor (MIS-2503-015V). The electrodes are 1.5mm in diameter and 4mm apart measuring from the center of the electrode. Suction holes are 2mm in

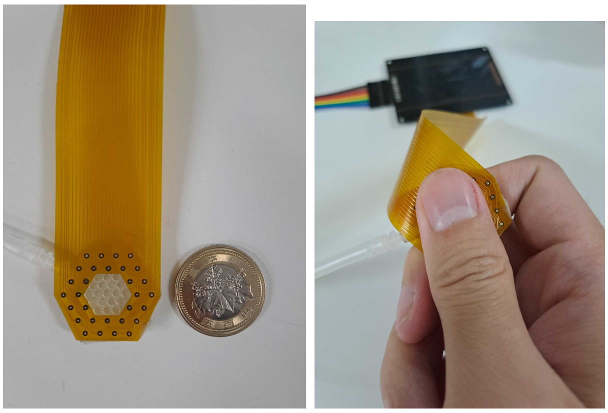

図 1: **Combination of electrotactile and suction pressure head**

diameter and 2.5mm apart measuring from the center of the hole.

The suction pressure head is connected to a flexible electrode sheet consisting of 30 electrodes arranged in a hexagonal manner with a hole in the middle for the suction pressure head which was attached by a double-sided tape.

2.2 Software

A virtual environment was prepared in the Unity game engine, with a set of small rigid bodies that act as contact sensors in a hexagonal arrangement. Each sensor was displaced from its arrangement on contact and may conform to the object's shape as be seen in Fig. 2. The displacement from its original position was interpreted as the force exerted. The refresh rate of the Unity software is set to 60 Hz.

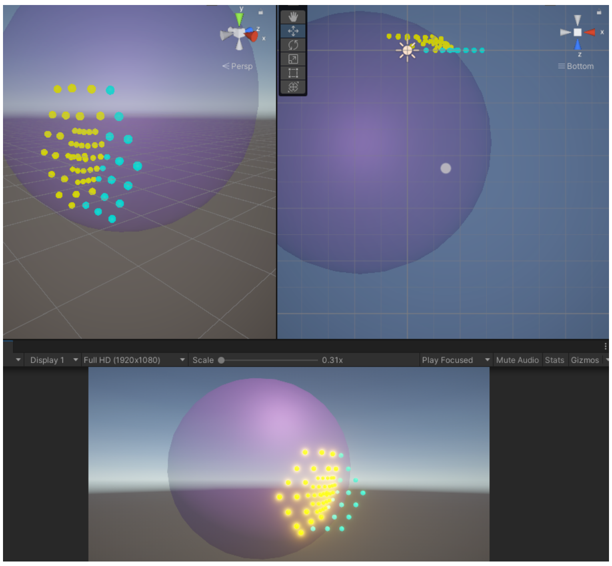

図 2: **Contact sensors partially submerged onto virtual object and activate haptics**

2.2.1 Suction Pressure

For suction pressure, the amount of contact sensors that detected force is averaged and is then translated to the pressure inside the suction pressure head such that a lower pressure causes a higher suction force. The maximum suction pressure value is -300 hPA in order to achieve a reasonable response time of 60ms [4]. Note that all holes are controlled by a single air pump and valve, and hence it cannot present spatial pattern.

2.2.2 Electrotactile Stimulation

For electrotactile stimulation, each sensor corresponded to each electrode in its appropriate position. Electrical current polarity was set to anode and the pulse width is set at 50 Hz, based on a previous study [2], and the pulse height was adjusted according to the participant's tolerance.

There are two modes of electrotactile stimulation: continuous mode and impact mode. The reason for including impact mode, especially as the ideal mode, firstly was to simulate the adapting period of the tactile receptors as the nerve firing rates decrease over time on stimulation [8]. The other reason was to simply reduce the period of use of electrotactile stimulation to avoid discomfort.

Continuous mode is a straightforward implementation of electrotactile stimulation in which the force exerted is directly translated to stimulation strength.

For impact mode, the impulse force exerted determines the stimulation strength and decays 0 stimulation within roughly 1.5 seconds on impact. This is achieved by accumulating the difference of force between frames of the application. The function used for the decaying was Unity's Mathf.Lerp function, defined as follows:

$$Lerp(a, b, t) = a + (b - a)t \tag{1}$$

In this case, a is the current stimulation strength, b is the target value (permanently set to zero) and t is the interpolation speed which was set to an arbitrary value of 4 multiplied by the time taken between frames to avoid potential framerate variance.

3. Experiment

The experiment was approved by the ethics committee of the authors' institution.

The goal was to evaluate the system's performance in providing a convincing and stronger touch sensation with little discomfort. The hypothesis is that within a system that combines both suction pressure and electrotactile stimulation, the initial impact of the contact phase can be improved by electrotactile stimulation, while the sustained pressure sensation is supported by suction pressure, and the discomfort of electrotactile stimulation can be minimized by decaying its strength after impact.

Five systems were compared: suction pressure (Suction), electrotactile impact stimulation (ElectroImpact), electrotactile continuous stimulation (ElectroContinuous), suction pressure with electrotactile impact stimulation (Suction ElectroImpact), and suction pressure with electrotactile continuous stimulation (Suction ElectroContinuous). The order of the systems presented was randomized.

Ten Participants were recruited, consisting of eight men and two women of age 21-29 (average 23 years, SD = 2.4, two left-handed). The experiment took 20-30 minutes per participant.

Before starting, each participant had their finger position adjusted to ensure the suction pressure value could consistently maintain below -200 hPa, and the pulse height of the electrotactile stimulation is calibrated to the user's maximum threshold before feeling pain.

The experiment consists of a virtual environment with a ping-pong ball-sized sphere positioned in front of the contact sensors that represent the user's finger. Every second, the ball approached to touch the user's finger for one second and returns to its original position. While the ball moved, white noise was played to mask any noise by the device. Participants were allowed to look at the screen. This motion is repeated for 4 times for each system and participants were asked 3 questions on a 7-point Likert scale (one = not at all similar, seven = completely similar). The questions were:

- Realism: Does sensation match user's expectation?
- Strength: How strong is the sensation?
- Discomfort: Is it pain or uncomfortable?

4. Results and Discussion

Statistical analysis for realism and discomfort values was carried out using SPSS. A two-way repeated measures ANOVA was applied to analyze the perceived weight differences between the stimulus conditions. A post hoc test using the Bonferroni method was also conducted to investigate the differences between conditions.

Fig. 3 shows the results of realism and discomfort reported by all participants in the simple contact sensation experiment.

There was a significant difference ($p = 0.03$) for realism only in ElectroContinuous against Suction ElectroImpact. Another minor observation was that Suction ElectroImpact was that it had the highest median and quartile values. Alongside the lack of significant difference for Suction ElectroContinuous against other modes.

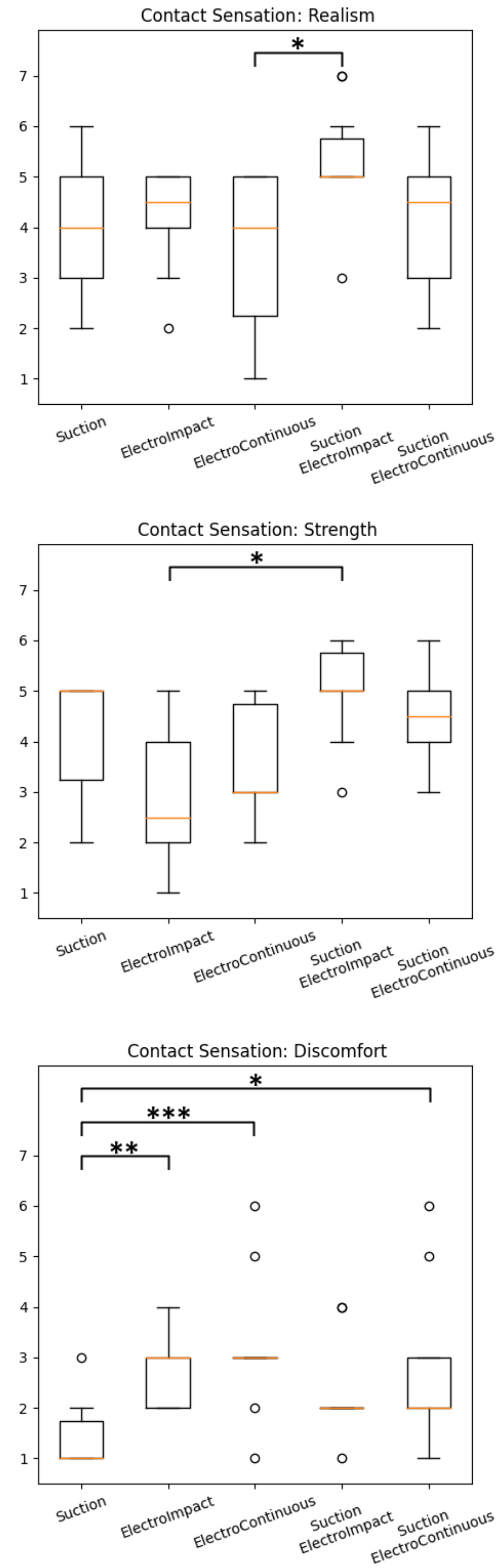

図 3: Likert scale scores for Simple Contact Sensation. (Top) Realism of each stimulation (Meddle) Strength of each stimulation (Bottom) Discomfort of each stimulation ∗: $p < 0.05$, ∗∗: $p < 0.01$, ∗∗∗: $p < 0.001$

This suggested that the use of electrotactile stimulation to simulate the nerve's adapting period [8] was a better representation of impact sensation and suction pressure provided a better prolonged touch sensation.

There was also a significant difference ($p = 0.019$) in strength perceived for ElectroImpact against Suction ElectroImpact. This could be explained by the fact that after electrotactile stimulation decays to zero, there was no stimulation to the finger despite being in contact. Suction ElectroImpact also had the highest median (although tied with Suction) and quartile values, which is interesting when considering that Suction ElectroContinuous technically had more stimulation overall. This suggested that, to an extent, the contrast of stimulation had a larger impact than the stimulation value itself when conveying pressure strength.

There were significant differences in Suction against both electrotactile only stimulations ($p = 0.007$ and $p < 0.001$) as well as against Suction ElectroContinuous ($p = 0.019$). Although SuctionElectroImpact showed no significant differences against both pure electrotactile stimulations, there was also an interesting lack of significant difference between Suction and SuctionElectroImpact. This suggested that adding electrotactile stimulation to suction pressure stimulation did not produce significant amounts of discomfort, and the existence of suction pressure had the potential to slightly reduce discomfort.

5. Conclusion and Future Work

A device combining suction pressure and electrotactile stimulation was developed to create a compact haptic device with high spatial and temporal resolution. Results showed that suction pressure with electrotactile stimulation that decays on impact could potentially provide the most realistic and strongest contact sensation, with no major detriments to causing discomfort when compared to just using electrotactile stimulation.

Other tactile sensations will be implemented to further utilize its spatial resolution such as softness presentation, moving textures, and a grip threshold sensation. Softness presentation can be achieved by presenting a wider contact area with electrodes [9]. Surface movement can be presented by combining moving patterns by electrical stimulation and pressure force by air suction [10]. A grip threshold sensation can be represented by producing a difference in stimulation strength between the contact area of an object on a finger which is divided into a sticking area and a "partial slip" area [11].

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