# Presentation of Slip Sensation Using Suction Pressure and Electrotactile Stimulation

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**Abstract.** The accurate detection of incipient object slippage is essential for grip control. This study aimed to replicate the sensation of losing grip by simulating a 'partial slip' phenomenon, in which the outer area of a contact point fluctuates slightly while the center of contact stays still. Two types of stimulation methods were used: electrotactile stimulation, chosen for its superior spatial and temporal resolution, which facilitates the precise replication of the partial slip area; and air-suction stimulation selected for its stable pressure sensation. We conducted an experiment to evaluate the effectiveness of each stimulation method, both independently and in combination, in terms of their ability to realistically convey the sensation of slippage, including the perceptual clarity of the slip occurrence and its direction. Results showed that the electrotactile stimulation was proficient in presenting distinct sensations of slippage and its direction while also providing some realism. Moreover, it was observed that the incorporation of suction notably enhanced the realism of the tactile sensation, particularly when used in conjunction with electrotactile stimulation.

**Keywords:** Electrotactile · Haptics · Partial Slip · Suction Pressure.

## 1 Introduction

The presence of slippage sensations plays a key role in our ability to reliably manipulate objects through grip control with our hands. Such detection enables precise control of grasping force, minimizing it to the requisite level needed to maintain a stable hold on an object. This incipient slip is predominantly perceived through cutaneous sensory feedback. Notably, this type of slippage typically initiates at the periphery of the skin-object contact area while the central region remains stationary, a condition often termed as 'partial slip' [5,7]. Research has posited that the detection and management of partial slip are crucial in facilitating dexterous object manipulation and in the regulation of grip force [7].

The objective of this study is to emulate the partial slip phenomenon through the strategic integration of two distinct tactile presentation modalities. The first modality, electrotactile stimulation, entails the application of an electrical current to the skin, thereby activating sensory nerve endings. Its most notable attributes include high spatial and temporal resolution, affording precise control over the localization and timing of stimuli [1,3,8]. This makes the electrotactile stimulation an excellent candidate for presenting slip sensations and could effectively signal the onset of an object's slip and convey directional information about the slip event [6], thereby contributing to the clarity of a slip sensation.

The second modality, suction pressure stimulation, generates a pressure sensation through the application of air suction that deforms the skin. This technique is especially adept at producing sustained pressure sensations [2,4]. It may be occasionally perceived as a sensation of pressure rather than suction [4]. A limitation of air suction stimulation lies in its lower temporal resolution, making it less effective for conveying sensations of rapid impact. Consequently, it is deemed suitable for simulating stable contact in the central region of the grip, thereby augmenting the realism of the slip sensation.

## 2 Implementation

### 2.1 Hardware

Fig. 1 illustrates the hardware configuration of the apparatus for suction pressure and electrotactile stimulation. For each part, an ESP32 microcontroller was used to communicate with a PC via USB. The apparatus comprises a dual-stimuli head, which accommodates both suction pressure and electrotactile modalities and has a mass of 5 grams. The overall weight of the device for a single finger, exclusive of the cables required for connection, is 160 grams. For this study, two heads were employed to administer stimuli to the index finger and thumb.

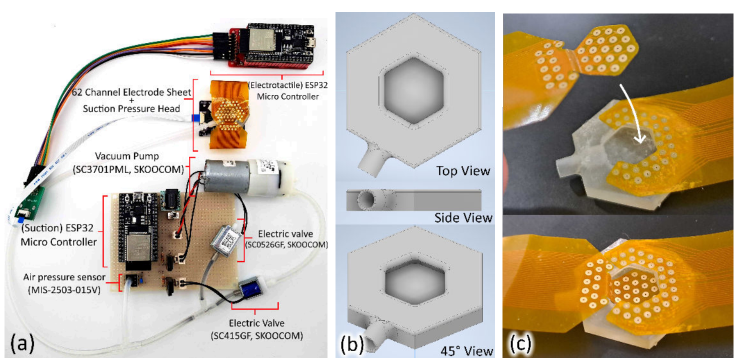


**Fig. 1.** (a) Suction pressure and electrotactile stimulation hardware setup for a single finger (b) Suction Pressure head (c) Method of combining electrotactile stimulation and suction pressure by pasting the electrodes onto the suction pressure head

The suction pressure module was based on previous work [2], with a newly designed suction pressure head using an optical 3D printer (Form3, FormLabs) and using Elastic Resin as the material with a singular suction hole with a hexagonal shape with equal sides of 6mm. The pressure inside the suction pressure head was controlled by 2 electric valves (SC0526GF, SKOOCOM and SC415GF, SKOOCOM), vacuum pump (SC3701PML, SKOOCOM), and air pressure sensor (MIS-2503-015V).

Two flexible electrode sheets, featuring electrodes arranged in a hexagonal configuration, were affixed to the suction pressure head using double-sided adhesive tape. Each electrode possessed a diameter of 1.5 mm and was positioned at a center-to-center distance of 2.4 mm from adjacent electrodes. The electrical current polarity was configured as anodic, with the pulse width established at 50 $\mu$s, and the repetition frequency at 90 Hz, as determined by prior research [1].

### 2.2 Haptic Rendering Method

The Unity game engine was used to host the simulation of pinching and elevating a virtual object using two fingers. The software operated at a refresh rate of 60 Hz. In this environment, each finger was represented by a set of small rigid bodies that acted as contact sensors in a hexagonal arrangement that curved outward. A dynamic attraction mechanism, employing a 'god-object' (an abstract point in space signifying the sensor's ideal position), was implemented. Here, a spring-like force governed the movement of sensors, intensifying as the distance from the god-object increased.

Each sensor corresponded to its respective electrode, positioned accurately as per the real-world configuration. Sensors representing the electrodes within the suction region contributed collectively to the overall suction pressure. Negative air pressure was modulated based on the spatial deviation between the god-object and the sensor's displaced position, with larger displacements generating greater suction forces. This principle extended to lateral movements, thereby replicating the skin's traction effects.

Electrotactile stimulation intensity was determined by the differential velocity between the object and the sensors. Greater discrepancies in speed resulted in heightened electrotactile sensations. The sensors' spherically convex arrangement, akin to a human fingerpad, inherently allowed for partial slippage at the periphery during contact within the simulation. This organization of sensors to be concave allows for emulation of natural interactions with objects.

## 3 User Study

The objective of this experiment was to systematically assess the attributes of two stimulation modalities, both in isolation and in combination, focusing on the authenticity of the slip sensation, its perceptual clarity, and the discernibility of the slip's direction.

It was hypothesized that electrotactile stimulation, as a singular modality, could effectively signal the onset of an object's slip and convey directional information about the slip event, which are based on existing examples such as the research of Okabe et al [6]. Concurrently, judging from the effective pressure sensation from the effective skin deformation produced by suction pressure [2], it was posited that the integration of suction pressure would augment the realism of the slip sensation, primarily by emulating the pressure experienced during object grasping and simulating cutaneous deformation concurrent with the slip.

This experiment encompassed the comparison of three stimulation conditions: suction pressure only, electrotactile only, and a combined application of both stimuli. Additionally, a control scenario, characterized by the absence of any stimulation during contact, was also incorporated. The experiment was approved by the ethics committee of the authors' institution.

### 3.1 Experiment Setup

The experimental setup employed the Meta Quest 2 Virtual Reality Headset with its right controller to which the suction pressure and electrotactile devices were attached. Participants were able to freely move the sensors using the positional tracking of the controllers and perform a pinching motion by pressing the controller's trigger button.

Prior to the experiment per participant, the intensity of the electrotactile stimulation was calibrated for each finger to the maximum stimulation threshold before pain or discomfort could be felt according to the participant. Steps were also taken to ensure the perceived stimulation strength was uniform, and if an imbalance were felt, the intensity would scale down to match the finger with the lower stimulation strength according to the participant.

The virtual environment was comprised of three distinct cubes, differentiated by their mass. These cubes were assigned mass parameters of 10, 20, and 30 within the Unity's Rigidbody component. However, for enhanced relatability, these were ostensibly labeled as "1kg," "2kg," and "3kg."

Participants were instructed to engage with the three cubes by freely touching and lifting them for a duration of one minute for each of the specified stimulation modes. To obscure any auditory cues emanating from the actuation of suction pressure, white noise was played throughout the interaction. After the one-minute interaction, participants were requested to evaluate their tactile experience on a 7-point Likert scale, with 7 representing a strong agree to the item, while 1 representing a strong disagree to the item, on three aspects: the realism of the tactile sensation, the clarity of the slip sensation, and the distinctness of the slip direction. Each stimulation mode was subjected to four trials, with the sequence being pseudo-randomized to avoid excessive repetition of any one condition. We recruited twelve participants (nine males, three females, average age = 24.75, SD=2.8) the University of Electro-Communications. The study took about 30 minutes to complete per participant.

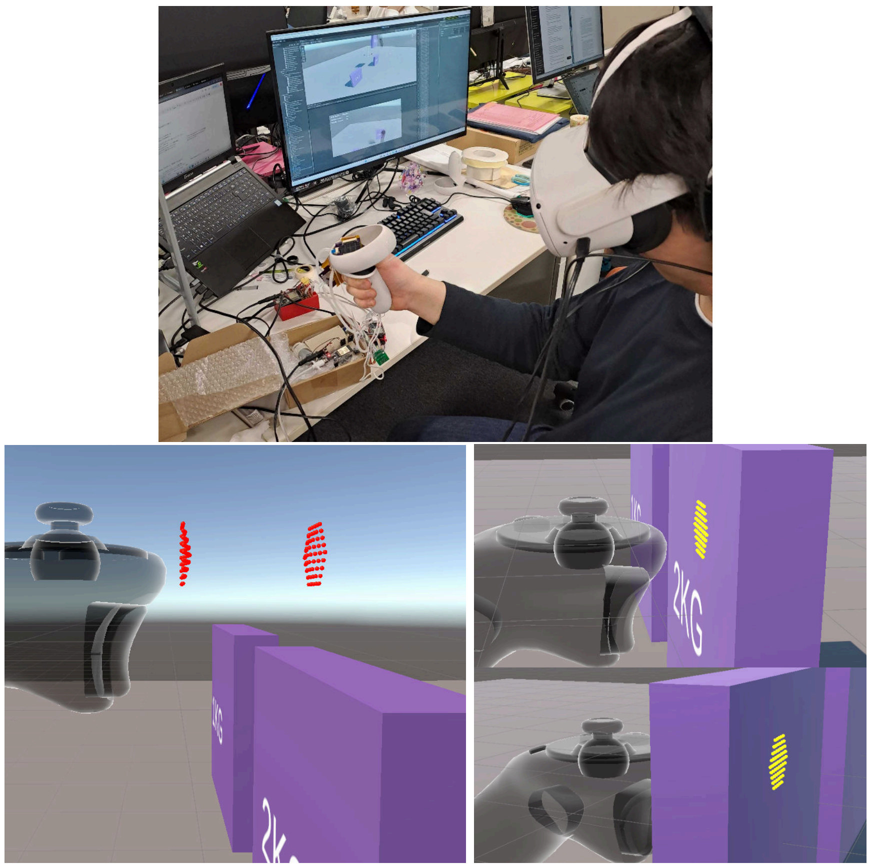


**Fig. 2.** (Top) Experimental setup using the Meta Quest 2 (Bottom left) Virtual environment with sensor before pinching (Bottom right) Virtual environment with sensor after pinching

### 3.2 Results and Discussion

The aggregated experiences resulting from four repetitions of each stimulation mode per participant were averaged to generate a composite score for each evaluative criterion, as illustrated in Fig. 3.

Given the ordinal scale format of the questionnaire data, it necessitates treatment as nonparametric. The Friedman test revealed a significant effect of electrotactile stimulation alone compared to no stimulation concerning slip clarity and directionality ($p < 0.001$). Post-hoc analysis, employing Bonferroni correction, further demonstrated significant differences between electrotactile stimulation alone and no stimulation ($p < 0.01$). These findings underscore the efficacy of electrotactile stimulation in enhancing both slip perception clarity and directional accuracy, aligning with our initial hypothesis regarding the conveyance of slip information through electrotactile stimulation. This also corroborates findings from a prior study indicating that electrotactile stimulation induces slip illusion [6].

Additionally, the Friedman test unveiled a significant disparity in the impact of suction pressure on realism compared to the no-stimulation condition ($p < 0.01$), with subsequent Bonferroni correction confirming a significant difference ($p < 0.05$). This suggests that the presence of suction pressure significantly enhances the perception of realism, in line with our hypothesis. However, it's noteworthy that there was no significant difference between sole electrotactile stimulation and the combined stimulation condition. Yet, the considerably stronger significant differences observed between combined stimulations and no-stimulation conditions (Bonferroni corrected values at $p < 0.001$) suggest that electrotactile stimulation also contributes to a sense of realism.

Furthermore, despite the clear enhancement of realism provided by suction pressure stimulation, it did not contribute to the clarity of slip direction. This implies that while directionality may be a crucial cue for object manipulation and preventing objects from slipping, it may not necessarily be pivotal for enhancing realism. The aggregated experiences from the four repetitions of each stimulation mode per participant were averaged, culminating in a composite score for each evaluative criterion, as depicted in Fig. 3.

Currently, our work has several limitations. Although the configuration of the virtual sensors was deliberately designed to simulate partial slip, the precise parameters and the extent of their curvature that affect the stimulation strength of the electrodes were not exhaustively explored. The values for these attributes were selected arbitrarily rather than through systematic investigation.

## 4 Conclusion and Future Works

In summary, this research endeavored to evaluate the efficacy of suction pressure and electrotactile stimulations in replicating a slip sensation. Our findings indicate that suction pressure significantly contributed to the realism of the slip sensation. Conversely, electrotactile stimulation excelled in providing acute

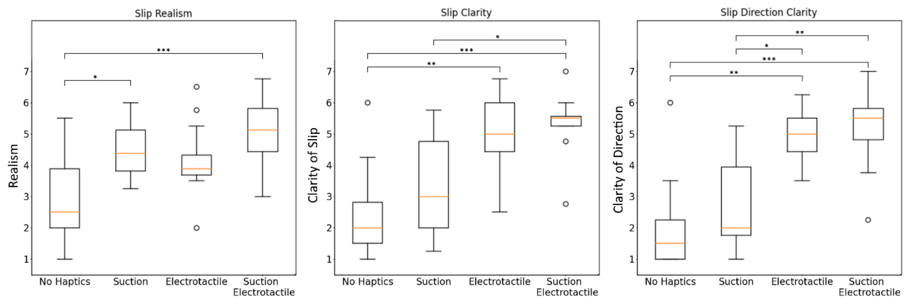


**Fig. 3.** Averaged Likert scale scores for Slip Sensation with Bonferroni corrected p values. (Left) Realism of each stimulation (Middle) Clarity of each stimulation (Right) Clarity of slip direction of each stimulation. $*$: $p < 0.05$, $**$: $p < 0.01$, $***$: $p < 0.001$

awareness of the imminent slip of an object, along with discerning the direction of said slip. While electrotactile stimulation alone imparted a moderate sense of realism, its effectiveness appears to be substantially augmented when combined with suction pressure.

As a progression in our research, we aim to conduct an in-depth investigation into the optimal variation in stimulation intensity between the central and peripheral areas of the contact zone. This study will focus on more accurately simulating the nuances of partial slip sensations

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