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Sebastian Vizcay, Panagiotis Kourtesis, Ferran Argelaguet, Claudio Pacchierotti, Maud Marchal. Design, evaluation and calibration of wearable electrotactile interfaces for enhancing contact information in virtual reality. *Computers and Graphics*, 2023, pp.1-15. 10.1016/j.cag.2023.01.013 . hal-03991492

HAL Id: hal-03991492

<https://inria.hal.science/hal-03991492>

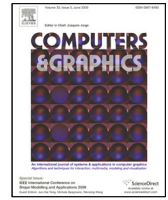
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Design, Evaluation and Calibration of Wearable Electrotactile Interfaces for Enhancing Contact Information in Virtual Reality

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ARTICLE INFO

Article history:

Received February 13, 2023

Keywords: Electrotactile Feedback, Virtual Reality, Human Computer Interaction

ABSTRACT

Electrotactile feedback is a convenient tactile rendering method thanks to reduced form factor and power consumption. Yet, its usage in immersive virtual reality has been scarcely addressed. This paper explores how electrotactile feedback could be used to enhance contact information for mid-air interactions in virtual reality. We propose an electrotactile rendering method which modulates the perceived intensity of the electrotactile stimuli according to the interpenetration distance between the user's finger and the virtual surface. In a first user study (N=21), we assessed the performance of our method against visual interpenetration feedback and no-feedback. Contact precision and accuracy were significantly improved when using interpenetration feedback. The results also showed that the calibration of the electrotactile stimuli was key, which motivated a second study exploring how the calibration procedure could be improved. In a second study (N=16), we compared two calibration techniques: a non-VR keyboard and a VR direct interaction method. While the two methods provided comparable usability and calibration accuracy, the VR method was significantly faster. These results pave the way for the usage of electrotactile feedback as an efficient alternative to visual feedback for enhancing contact information in virtual reality.

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1. Introduction

Immersive virtual reality (VR) is becoming a common platform for education and training, where precision and accuracy during manipulation of virtual objects are key aspects [1, 2]. Visual feedback is particularly important for contact accuracy and precision [3]. However, when kinesthetic feedback is not available, if no other measures are adopted, the user's avatar might interpenetrate the virtual content, which could have a negative impact on the accuracy, precision, and the realism of the interaction. To avoid such an undesired behavior and facilitate mid-air interactions in VR, a popular technique is

the use of the *God-object Method*, where the virtual hand is constrained by the collision with the virtual object(s) [4, 5]. When using the *God-object Method*, there is a decoupling of the visual representation of the user's avatar (e.g., the virtual hand) from its actual position when the avatar is constrained on the virtual object's surface whereas the actual tracked position would be inside the object [6]. Moreover, when using this popular technique, while the virtual hand is rendered on the collided object's surface, the user's physical hand is still able to move in the real environment unconstrained (i.e., penetrating the virtual object's coordinates), which results in failing to perceive the inaccuracy and imprecision of the contact [4, 5].

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A cost effective solution is to use tactile feedback to render the contact. Tactile feedback devices can provide vibrotac-

tile, pressure, or skin stretch feedback sensations [7]. However, these displays need to embed one or more mechanical actuators that move an end-effector in contact with the user's skin, limiting their wearability, portability, and comfort [7]. In this respect, electrotactile haptic stimulation has been recently recognized as a promising technique to provide rich tactile sensations across the hand or arm through a single wearable actuator [8]. Applying electrical stimulation to the skin elicits tactile sensations by directly activating the sensory nerves, de facto bypassing the skin mechanoreceptors. The electrical current produces a local depolarization near the skin, triggering an action potential. The current is generated by two or more electrotactile interfaces (electrodes). With respect to other tactile solutions, electrotactile stimulation only requires very thin electrodes placed at the sensation point (e.g., the fingertip), providing a wearable and comfortable solution to tactile haptics.

Nevertheless, despite its promising features, the benefits of electrotactile feedback in VR interactions are still under-investigated. In a VR pilot study (N=3), electrotactile feedback provided haptic information pertinent to heat, jolt, and texture [9]. In a small size user study (N=10), electrotactile feedback was able to generate tactile sensations such as roughness, friction, and hardness [10]. In a VR user study (N=19), electrotactile feedback was successful in improving grasping [11]. However, an inappropriate application of electrotactile feedback may elicit undesirable effects such as absence of sensation, skin irritation, burns, electric shock, and discomfort [12]. A personalized calibration of electrotactile feedback, where the intensity of the electrotactile feedback is adjusted to the personal sensational and discomfort thresholds of the user, may prevent these adverse effects [13].

This paper presents the design and evaluation of an electrotactile feedback rendering method to enhance contact information for mid-air interactions with virtual objects in virtual reality. The proposed method modulates the perceived intensity of the electrotactile stimuli according to the interpenetration distance between the user's finger and the virtual surface (i.e., the distance between the real and the virtual hand). Moreover, as the calibration phase is a key element to provide compelling and effective feedback, this paper further explores the benefits of embedding the calibration procedures directly in VR to reduce the calibration time and increase the user's comfort. Precisely, we propose a calibration method that can be integrated directly into the virtual environment. In summary, the main contributions of our work are:

- The design of an electrotactile feedback technique for enhancing contact information in VR.
- A user study (N=21) for evaluating electrotactile interpenetration feedback's performance against no interpenetration feedback, a visual interpenetration feedback, and a visual-electrotactile interpenetration feedback.
- A user study (N=16) evaluating two different calibration procedures, a keyboard-based and a VR-based method, assessing the calibration time and the dynamic range.

The paper is structured as follows, Section 2 presents an overview of the state of the art on wearable haptics, electrotactile feedback and contact rendering in VR. Then, Section 3

describes the proposed electrotactile system for interpenetration rendering. Section 4 describes an experiment assessing the advantages and disadvantages of the proposed electrotactile system. Section 5 describes and evaluates a VR-based calibration method conceived to speed up the calibration process. Finally, the paper concludes with a global discussion and the concluding remarks.

2. Related work

2.1. Wearable tactile feedback in VR

Popular techniques to provide rich wearable tactile feedback are through moving platforms, that can orient and/or translate on the skin, pin-arrays, shearing belts and tactors, pneumatic jets, and balloon-based systems [7]. Frisoli et al. [14] were among the first to present a fingertip tactile display for improving curvature discrimination using a moving platform. Their system was composed of a parallel platform and a serial wrist. Gabardi et al. [15] improved this device and applied it in VR interaction. The pose of the user's finger was tracked through external optical sensors and collisions between the finger avatar and the virtual surface were rendered by the device. Minamizawa et al. [16, 17] presented a wearable fingertip device for weight rendering in VR. It consisted of two DC motors moving a belt in contact with the user's fingertip. A similar device was also used in [18] for multi-finger manipulation of objects in VR, in [19] for controlling multi-robot systems in VR, and in [20, 21] for augmenting tangible objects in VR. Similarly, Girard et al. [22] developed a wearable fingertip device capable of rendering 2-DoF skin stretch stimuli in VR. The considered use cases comprised tapping on a virtual bottle and feeling the texture and weight of a virtual object.

2.2. Electrotactile feedback

Due to the difficulty in designing effective interaction paradigms, electrotactile interfaces have rarely been used in VR scenarios. Jorgovanovic et al. [23] evaluated the capabilities of human subjects to control grasping force in closed loop using electrotactile feedback. It was tested in an experiment of virtual robotic grasping. More recently, a pilot study by Pamungkas and Ward [9] used electrotactile stimulation on the hand to convey the sensation of contacts in VR. Use cases comprised playing with a virtual bouncing ball, setting up a camp fire, feeling different surface textures, and shooting a gun. Hummel et al. [11] developed an electrotactile delivery system composed of a small tactor with eight electrodes for each finger. They tested it in three VR assembly tasks for remote satellite servicing missions, which included pressing a button, switching a lever switch, and pulling a module from its slot. In another pilot study, Sato et al. [24] combined electrotactile feedback with a PHANToM Omni kinesthetic display for rendering spatial distributed touch sensation. Finally, Yem et al. [25] employed electrotactile stimulation to elicit flexion/extension illusory movements to the user's fingertip. Doing so, the system was able to induce haptic feedback sensations, providing information about virtual objects' stiffness and stickiness properties.

A major challenge for electrotactile interfaces is the calibration of the electrotactile parameters for a given user. A number

of studies have attempted to automate and improve the calibration process. Gregory et al. [26] developed a circuit model for identifying and classifying the parameters of the skin-electrode interface. Similarly, Fadali et al. [27] used a model with fuzzy logic for detecting preferences pertinent to tactile sensations. Also, a real-time feedback loop was developed by Kajimoto [28], destined to monitor the skin's impedance in order to make the system regulate the electrotactile feedback's intensity. Comparably, Akhtar et al. [29, 30] delivered models for measuring the skin's impedance and adjusting the electrotactile feedback parameters. Rahimi et al. [31, 32] implemented an automatic recurrent calibration process for legally blind users of a Braille text-reading assistive system. Finally, Isakovic et al. [33] strived to offer an optimization of the calibration process for providing the users with a personalized electrotactile feedback.

2.3. Contact information in VR

In the last years, researchers focused on the sensation of making and breaking contact [34, 35, 36, 37, 34], as it is proven to be an important factor for immersion in VR. Kuchenbecker et al. [38] endowed a desktop kinesthetic interface with a passive tactile end-effector. The kinesthetic feedback provided by the desktop device bends the internal springs of the tactile end-effector and brings a shell in contact with the user's finger, providing the sensation of making/breaking contact with the virtual object. In a similar fashion, Gonzalez et al. [39] attached a ring of optical sensor to the end-effector, being able to measure the distance of the fingertip from the ring and adjust the transition between free space and contact. Finally, Prachyabrued and Borst [6] evaluated the impact of visual feedback in pinch grasping a virtual object, where the best performance was obtained when showing both hand models (tracked and constrained) and when coloring the fingers of the object being grasped.

To the best of our knowledge, the effects of using electrotactile feedback for enhancing contact information in VR mid-air interactions has scarcely been studied.

3. Design of electrotactile interpenetration feedback

The tactile sensation elicited by electrotactile stimulation can be controlled by the parameters chosen for the design of the electrodes and the parameters of the delivered electrical signal [40, 41, 42, 43]. Individual pads in an electrode can be disabled or enabled (enabled as either cathode or anode) meanwhile signal's intensity, pulse width and frequency can be increased/decreased to apply some modulation. Pad selection determines the location where the stimulus is going to be applied.

Changes in the current intensity is the most common way to increase/decrease the strength of the sensation, but the feeling is highly variable across subjects and relatively small increases can quickly elicit uncomfortable sensations. Changes in the pulse width and frequency can also elicit changes in the perceived strength of the sensation, although less significantly than when altering the current intensity [44]. Changes in the frequency are also employed to increase/decrease the perceived speed of the stimulation.

Given the disadvantages of intensity modulation, we fixed the intensity value for each participant, chosen after a brief calibration so as to avoid any undesired uncomfortable/painful sensation. We chose pulse width modulation to control the strength of the sensation and frequency modulation to control its speed. We chose to place the electrodes at the fingertip, as it is the area of the body most often used for pointing, grasping, and manipulating objects [7]. To produce the stimulation at the center of the finger pad, we select an anode-cathode configuration with the widest possible dynamic range for the given electrode. As mentioned before, we modulate the electrotactile interpenetration feedback proportionally to the distance between the constrained user's fingertip avatar (i.e., the object surface) and its actual position as tracked by the system. In other words, both the perceived intensity and speed of the electrotactile sensation increase as the user's physical hand interpenetrates the virtual object.

To achieve this effect, the pulse width is modulated linearly from 200 μs to 500 μs . On the other hand, we considered the perception of frequency to be logarithmic [45] and we apply a gamma correction so as to linearize how fast the tingles are perceived. The proposed frequency modulation allows us to explore a range of frequencies from 30 Hz to 200 Hz, which is the maximum frequency of the device. Fig. 1 shows the two inputs with respect to the normalized interpenetration (1: maximum, 0: zero, see subsection 3.2 for the details). Choices regarding the range of stimulation and the active pads have been done after a short preliminary study, so as to provide the most comfortable tactile sensations to the finger pad.

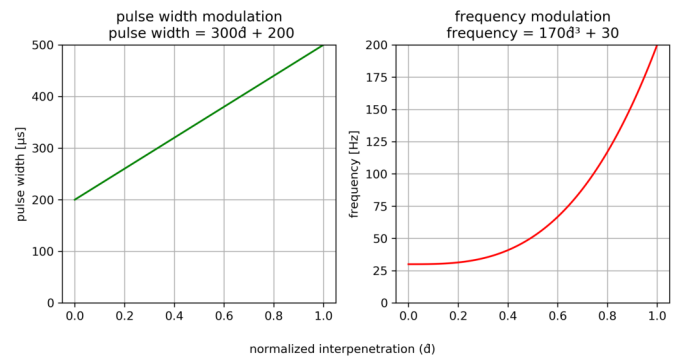


Fig. 1. electrotactile interpenetration feedback modulation via pulse width (left) and frequency (right).

3.1. Electrical stimulator and electrodes

Our custom electrotactile stimulator has 32 channels, to which up to 5 electrodes can be connected simultaneously. Each channel may be defined either as a cathode or as an anode. The stimulator produces a biphasic cathodic stimulation through square waves. Electrical intensity and pulse width can be set per each channel in the ranges of [0.1, 9] mA and [30, 500] μs , respectively. The stimulus frequency can be set in the range [1, 200] Hz.

We used electrodes whose cathodes are distributed in a matrix array of 2 rows by 3 columns, surrounded by two larger lateral anodes that are interconnected by a segment going through both rows of cathodes (see the insets in the top-left corner

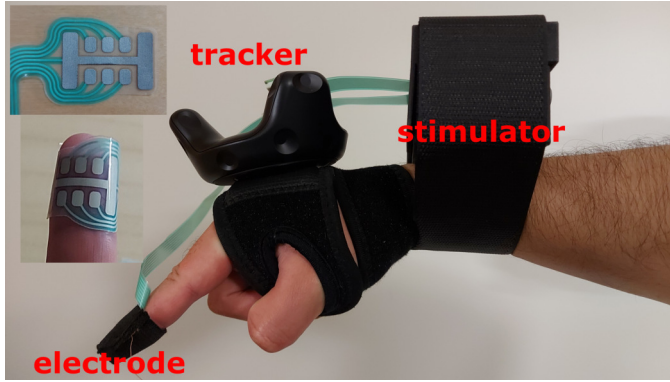


Fig. 2. Experimental apparatus. The electrical stimulator is attached to the forearm and the electrode is placed in contact with the finger pad. The two insets represent detailed views of the electrode. The user's hand is tracked by a HTC Vive Tracker.

of Figure 2). This particular layout has been designed to widen the dynamic range of sensations.

3.2. System design

The interpenetration of the finger avatar into the virtual content drives our pulse width and frequency modulation. After a series of pilot user studies, we determined that, for a cube of edge of 15 cm, 3 cm represents the maximum interpenetration achieved in most interactions. For this reason, we normalized the interpenetration d by this value, i.e., a normalized interpenetration \hat{d} of 1 means a true interpenetration into the virtual object of 3 cm.

The position of the participant's hand is tracked using a HTC Vive Tracker attached to the back of the hand. The *physics-based* hand avatar (physics-based as its interactions are handled by the physics engine) collides with the other objects in the virtual environment while trying to follow the position indicated by the tracker. As described at the beginning of section 3, this avatar resolves all virtual collisions and avoids any undesired virtual interpenetration. Whenever it comes into contact with a virtual object, its motion is constrained to stay on the object's surface, regardless of how much the user's hand moves into the object. As detailed above, this discrepancy between the user's real hand and its avatar drives our electro-tactile interpenetration feedback.

4. Contact experiment

4.1. Evaluation

This section describes a user study evaluating the proposed electro-tactile interpenetration feedback system. Our main objective was to assess the potential advantages and disadvantages of using electro-tactile interpenetration feedback while performing a task requiring a high level of accuracy and precision. In particular, we focused on a task in which the user is asked to contact a virtual surface with his/her index finger while minimizing the amount of interpenetration between the virtual surface and the real index finger. In such a task, when the virtual hand avatar cannot interpenetrate virtual surfaces, it is difficult for the user to precisely assess the amount of interpenetration

between his/her finger and the virtual surface without any additional feedback.

Our main hypothesis is that additional interpenetration feedback, either visual and/or electro-tactile, would increase the awareness of the user, effectively decreasing the amount of interpenetration. Yet, electro-tactile interpenetration feedback will provide a more coherent experience. In addition to consider the electro-tactile interpenetration feedback method presented in the previous section, for comparison purposes, we also modulated the availability of visual cues. First, we considered a visual interpenetration feedback technique. Second, we considered the interaction with two different virtual objects, a fully-opaque virtual cube and a wireframe-only cube. We considered the latter so as to limit the visual cues which could anticipate the contact with the virtual object.

Hence, the independent variable (IV) *Interpenetration Feedback* has four levels: 1) No Interpenetration Feedback; 2) Visual Interpenetration Feedback; 3) Electro-tactile Interpenetration Feedback, 4) Visual-electro-tactile Interpenetration Feedback (i.e., both interpenetration information is provided: visually and haptically). The four levels of the IV are examined in two object rendering methods: 1) fully-opaque and 2) wireframe-only. In the following, we detail how these techniques are implemented in our experimental study.

4.1.1. Experimental task

The task required participants to touch a virtual surface (a cube of size $15 \times 15 \times 15$ cm) which was located on a virtual table (see Figure 3). Participants started the experience in a seated position in front of said virtual table. The cube was placed on the user's left side, while a resting area was located on the user's right side. For each trial, participants were asked to start with their right hand in the resting area. Then, they were asked to reach precisely with their index finger the top side of the virtual cube while keeping a steady contact for three seconds. Finally, they were notified that they should return their hand back to the resting area. Participants were instructed to minimize the interpenetration between the virtual surface and their real index finger while ensuring a continuous contact with the cube. To ensure that all participants kept a consistent timing, auditory feedback (a short beep sound) was used to notify the users when they had to start the trial and when the three seconds of contact were achieved. During the whole interaction, participants were asked to keep their hand in a closed fist, with the index finger fully extended for facilitating a similar posture and an approximate collocation between the physical and the virtual hand. The experimenter was prompting each participant to have this posture when a new block was starting, while during the breaks between the blocks, the participant could have a rest and move her/his hand and fingers freely or just relax, which assisted with avoiding a postural fatigue.

4.1.2. Electro-tactile interpenetration feedback calibration

The calibration of the electro-tactile interpenetration feedback is a key step to ensure that all participants perceived a consistent tactile feedback. As the calibration cannot be done automatically, participants were asked to calibrate the intensity of the electro-tactile interpenetration feedback multiple times throughout the experiment. If the calibration is not done per each user,

parameters such as the skin's conductivity and/or a tolerance could result in stimuli that are not perceived (i.e., too low intensity) or uncomfortable or even painful (i.e., too high intensity).

The right range of current intensity was determined using the method of limits. Starting from a low intensity value, participants increased the intensity by pressing a key in a keyboard using steps of 0.1 mA. This incremental procedure continued, step by step, until the participant confirmed that the electro-tactile feedback was perceived, defining his/her sensation detection threshold. Then, the incremental approach continued until the participant confirmed that the electro-tactile feedback caused discomfort, defining his/her pain/discomfort threshold. Similarly, starting from a high intensity value, the intensity was decreased considering steps of 0.1 mA. This starting high intensity value was defined as the 3rd quartile of the range between the detection and pain/discomfort thresholds. This decremental procedure continued, step by step, until the participant confirmed that the electro-tactile feedback was not perceived anymore.

During the entire calibration process, the signal frequency was set to 200 Hz and the pulse width to 500 μ s. These values were chosen as they represent the strongest stimulation that could be achieved along the experiment at max finger interpenetration. The final intensity value that was used throughout the experiment was calculated from a linear interpolation between the detection and discomfort thresholds. We chose an intermediate value between these thresholds, as it would result in a perceivable yet comfortable stimulus.

4.1.3. Participants and apparatus

A total of 21 individuals [age: $mean(SD) = 25.67(2.74)$; range = 23 – 33 years old; gender: 14 males, 6 females, and 1 non-binary] were recruited through an in-campus advertisement and a call on institutional email lists. 21 participants were familiar with using VR head-mounted displays (VR-HMDs), 10 participants had a previous experience with receiving tactile feedback in VR (predominantly vibrotactile), and only 2 had experienced electro-tactile feedback in the past.

An HTC Vive Pro HMD was used for immersion. The PC had an NVIDIA RTX 2070. An HTC Vive Tracker attached to the back of the palm (see Figure 2) and 2 Lighthouse base stations were used for tracking. See Figure 2 for the placement of electro-tactile stimulator, which weighed 300 g. A Velcro strap was used to hold the electrode. Its tightness was adjusted to achieve a comfortable yet firm placement of the electrode.

The VR application was built using Unity in conjunction with the SteamVR Unity plugin (see Figure 3). The collisions were directly handled by the SteamVR plugin and the Unity physics simulation. A blackboard was used for providing any critical information/instructions within the participant's field of view.

4.1.4. User representation and visual interpenetration feedback

The user could only see a visual representation of their right hand (avatar). As stated earlier, the hand avatar cannot go through the virtual object so as to better mimic a real interaction. The hand is always kept in a closed fist, with the index finger fully extended, which is the same pose we asked participants to keep while interacting with the cube (see Figure 4).

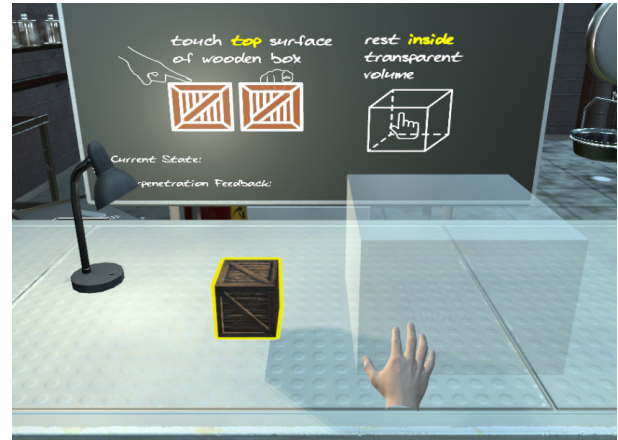


Fig. 3. Depiction of the subjective view of the user during the experiment. The user could touch the virtual cube placed on the top of the table on the left. The semitransparent cube on the right side defines the resting area. The blackboard in front of the user provided general information during the experiment.

An outline effect was used as visual interpenetration feedback (see Figure 4). Outline effects are commonly used to denote interactivity or selection [46, 47]. However, the implemented outline was dynamically rendered proportional to interpenetration's depth. The outline was parameterized using a scale factor and the size of the border. The scale factor went from $\times 1$ (edge of 15 cm^3) to $\times 1.2$ (edge of 18 cm^3). The border varied between 1 and 5 pixels (see Figure 4).

When both electro-tactile and visual interpenetration feedbacks are provided, a mismatch between the two modalities may result in a haptics' uncanny valley effect, which compromises the performance [48]. For this reason, the modification of border size and width of the outline was determined through a pilot study. The choice of these particular parameters aimed to ensure that, comparably to the electro-tactile interpenetration feedback, the perception of the "intensity" of the visual feedback is proportional to the size of the interpenetration.

4.1.5. Experimental protocol

This study received the approval of the authors' institution ethical committee. As it was carried out during the COVID-19 pandemic, a preventive hygiene and disinfection protocol was implemented. Participants signed an informed consent form prior to their participation and we briefly explained to them the principle of how electro-tactile feedback works, the type of sensations it can elicit and how the intensity needs to be calibrated. The set up consisted of a VR area, a table, and a chair. The table was co-located with the virtual table. A pre-exposure questionnaire was filled to acquire demographic data. Participants went through a tutorial for performing the experimental task. The execution of the trials were divided into two halves by a recalibration of the intensity. The experiment followed a latin square design, 4 types of interpenetration feedback \times 2 types of cube shading \times 2 experiment halves (i.e., $4 \times 2 \times 2$). Each experiment's half had 4 blocks, where each block consisted of 12 repetitions. In total, each participant performed 96 repetitions (i.e., 48 per experiment's half). In total, 3 calibrations were performed a) initial calibration: before first half; b) middle calibra-

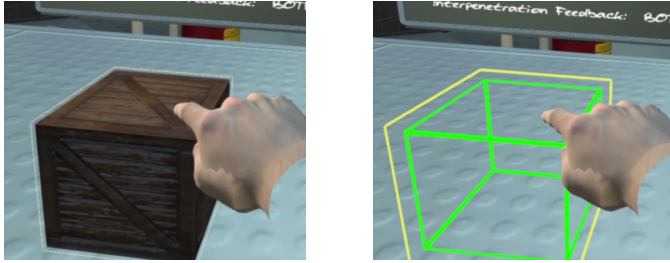


Fig. 4. Visual shading conditions (left & right) and visual interpenetration feedback (right).

tion: between first and second halves; c) final calibration: after second half. Finally, a post-exposure questionnaire was filled to acquire the participant's subjective ratings on the types of feedback, with a focus on electro-tactile interpenetration feedback.

4.1.6. Dependent variables and hypotheses

In order to answer the hypothesis of our experiment and considering the experimental task, we measured the following metrics: average (avg_d), standard deviation (std_d) and maximum (max_d) interpenetration during the three seconds in which the user was asked to remain in contact with the virtual cube surface. As we did not track the user's finger but the back of the hand, the interpenetration was computed by measuring the distance between the estimated position of the *real* fingertip in the virtual environment and the position of the avatar fingertip constrained on the surface of the cube. The interpenetration measures provide information regarding the awareness of the real interpenetration (accuracy) and their ability to keep a constant and not oscillatory contact with the virtual surface (precision). In this respect our hypotheses were:

- [H1] The addition of interpenetration feedback (either visual or electro-tactile) will increase the precision and the accuracy of the task.
- [H2] The combination of the visual and electro-tactile interpenetration feedback will result on the best precision and accuracy.
- [H3] Precision and accuracy will be higher for the fully shaded condition.
- [H4] Precision and accuracy will improve along the experiment due to learning effects.

The sensation and discomfort thresholds (in mA) were obtained during the three calibration processes. We expected that the thresholds will vary due to changes in skin conductivity or due to habituation. In this respect our hypothesis was:

- [H5] Sensation and discomfort thresholds will monotonically increase during the experiment.

Finally, the participants' subjective report were collected through a post-exposure questionnaire. The questionnaire is included as supplementary material. The questionnaire encompassed questions pertaining to the perceived usefulness, coherence, and resemblance with a real interaction of the electro-tactile interpenetration feedback, as well as some comparison

questions between the interpenetration feedback modalities. In this respect our hypotheses were:

- [H6] Electro-tactile interpenetration feedback will be reported as useful and coherent.
- [H7] There will be no significant differences between visual and electro-tactile interpenetration feedback in terms of usefulness, coherence, and/or resemblance.

4.2. Results

The homogeneity and normality assumptions were examined. The performance variables violated the normality assumption. The values were converted into logarithms since the variables' distributions were substantially positively skewed. No violation was then detected. The same amendments were made for the intensity values, which also violated the normality assumption. Finally, as the shading condition showed no significant results (which suggests the rejection of H3) and for the sake of clarity, the shading condition will not be considered in the results report. Thus, for the following analyses, the conditions were the type of interpenetration feedback and the "half" of the experiment (whether the trial was performed in the first half of the experiment, before the middle calibration, or after that in the second half).

A two-way repeated measures ANOVA was performed for each performance variable, as well as a post-hoc pairwise comparisons test respectively. When the sphericity assumption was violated, then the Greenhouse Geisser's correction was considered. Furthermore, a pairwise comparison was conducted to explore potential differences in the intensity values amongst the three calibrations (i.e., initial, middle, and final). Hedge's g and the ω^2 were preferred as they are more parsimonious and reliable metrics of effect sizes of the ANOVA and post-hoc comparisons respectively [49]. Also, a Pearson's correlational analysis was performed to investigate the presence of relationships between the intensity values and the performance variables. Finally, the post-exposure self-reports (Likert scale) provided by the participants were explored. A non-parametric pairwise comparison was implemented to examine the presence of differences on the questionnaire's items. The Bonferroni correction was implemented accordingly to the number of comparison's pairs in each analysis to amend p-values' inflation due to multiple comparisons. The descriptive statistics for all performance variables and the intensities, as well as the results for the maximum interpenetration are all included in the supplementary material for completeness.

4.2.1. Index finger interpenetration

Average Index Interpenetration — Accuracy. The ANOVA's outcomes indicated that all effects were statistically significant. The type of feedback produced a main effect of $F(1.97, 39.31) = 25.89, p < .001$ postulating a substantial difference amongst the feedback types. In line with H1, $\omega^2 = 0.54, 95\% CI[0.35, 0.66]$ suggests a very large effect of the type of feedback on average interpenetration (i.e., accuracy). In support of H4, the half of the experiment yielded an effect of $F(1, 20) = 31.74, p < .001$, suggesting a significant difference between the two halves of the experiment with a very

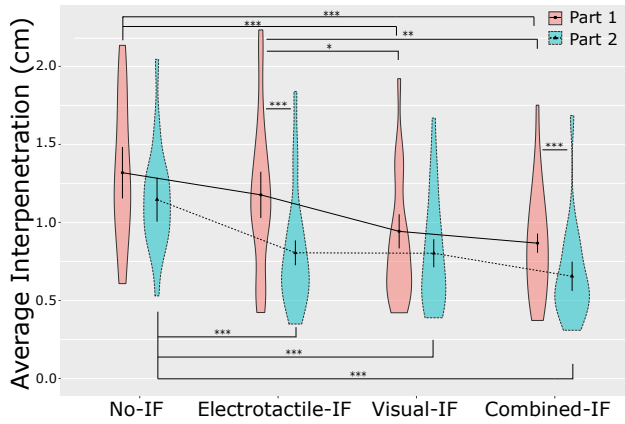


Fig. 5. Average Interpenetration in cm. Comparisons per Type of Feedback and Half of the Experiment. IF = Interpenetration Feedback.

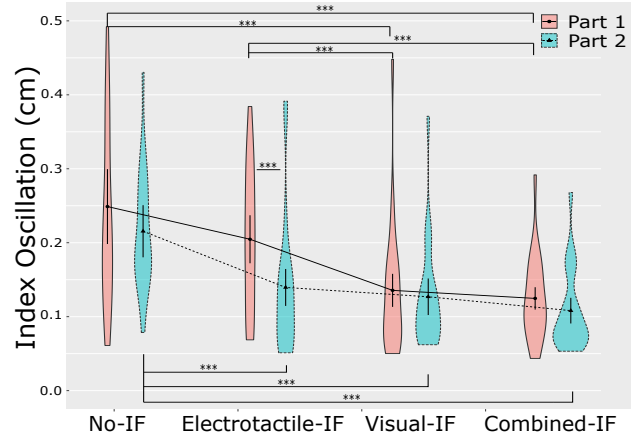


Fig. 6. Index Oscillation in cm. Comparisons per Type of Feedback and Half of the Experiment. IF = Interpenetration Feedback.

1 large effect size of $\omega^2 = 0.58$, 95% $CI[0.26, 0.75]$. The inter-
 2 action between the halves of the experiment and the types of
 3 feedback produced an effect of $F(2.11, 42.21) = 5.72$, $p = .006$
 4 indicating significant differences among the pairs between the
 5 types of feedback and the parts of experiment. An $\omega^2 = 0.18$,
 6 95% $CI[-0.01, 0.34]$ was yielded for these interactions indicat-
 7 ing that they have a large effect on the accuracy.

8 The post-hoc pairwise comparisons are displayed in Figure 5.
 9 The results support both **H1** and **H2**: use of interpenetration
 10 feedback (visual or electrotactile) will increase accuracy, while
 11 the combination of them will improve it even more. In the 1st
 12 half, the visual ($g = 0.90$, $p < .001$) and combined feedback
 13 ($g = 1.10$, $p < .001$) were substantially improved compared to
 14 the no-interpenetration feedback condition with a large effect
 15 in both comparisons. Also, the visual ($g = 0.52$, $p = .026$)
 16 and combined feedback ($g = 0.67$, $p = .002$) were substantially
 17 better than the electrotactile condition, with a moderate effect
 18 size in both comparisons. In the 2nd half, the visual ($g = 1.10$,
 19 $p < .001$), combined ($g = 1.69$, $p < .001$), and electrotactile
 20 interpenetration feedback ($g = 1.10$, $p < .001$), were significantly
 21 better compared to the no-interpenetration feedback condition,
 22 with a very large effect in every comparison. No further signifi-
 23 cant differences were detected in both halves. Furthermore,
 24 the electrotactile ($g = 0.86$, $p < .001$) and combined feedback
 25 ($g = 0.69$, $p < .001$) were significantly improved in the 2nd half
 26 compared to the 1st half, with a large and a moderate effect cor-
 27 respondingly. In contrast, the equivalent comparisons for the
 28 no-interpenetration feedback and visual interpenetration feed-
 29 back were not statistically significant. Notably, only the size of
 30 change for electrotactile interpenetration feedback was signifi-
 31 cantly greater than the size of change for the no-interpenetration
 32 feedback ($g = 0.64$, $p = .005$) and visual interpenetration feed-
 33 back ($g = 0.60$, $p = .010$), with a moderate effect size for both.

Standard Deviation Index Interpenetration — Precision.

34 The results of the ANOVA suggested statistically significant
 35 effects at .05 significance level. Supporting **H1**, the main ef-
 36 fect of the the type of feedback on index oscillations (i.e., pre-
 37 cision) yielded an effect of $F(1.88, 37.69) = 28.92$, $p < .001$,
 38 and of $\omega^2 = 0.57$, 95% $CI[0.39, 0.68]$ postulating significant
 39 differences between the diverse types of feedback with a very
 40 large effect size. Aligned with **H4**, the main effect for the half
 41

of experiment on the precision produced an $F(1, 20) = 9.32$,
 42 $p = .006$, and of $\omega^2 = 0.27$, 95% $CI[-0.01, 0.54]$ suggesting
 43 a significant difference between the two halves of the exper-
 44 iment with a large effect. The interaction among the diverse
 45 pairs derived from the halves of the experiment and the types of
 46 feedback yielded an interaction effect of $F(2.38, 47.66) = 4.30$,
 47 $p = .014$, and of $\omega^2 = 0.13$, 95% $CI[-0.03, 0.29]$ postulating
 48 significant difference between the diverse pairs with a large ef-
 49 fect size.

50 The post-hoc pairwise comparisons are illustrated in Figure
 51 6. The results appear to support both **H1** and **H2**. In
 52 the 1st half of experiment, the visual ($g = 1.06$, $p < .001$) and
 53 combined feedback ($g = 1.109$, $p < .001$) were founded sub-
 54 stantially greater than the no-interpenetration feedback condi-
 55 tion, with a very large effect in both comparisons. Also, the
 56 visual ($g = 0.79$, $p < .001$) and combined feedback ($g = 0.90$,
 57 $p < .001$) were found to be substantially better than the electro-
 58 tactile interpenetration feedback, with a large effect size in both
 59 comparisons. In the 2nd half of experiment, the visual ($g = 1.32$,
 60 $p < .001$), combined ($g = 1.71$, $p < .001$), and electrotactile
 61 interpenetration feedback ($g = 1.07$, $p < .001$), were found to be
 62 significantly better than the no-interpenetration feedback condi-
 63 tion, with a very large effect in every comparison. No further
 64 significant differences were detected in both halves. Further-
 65 more, only the electrotactile ($g = 0.74$, $p < .001$) was found to
 66 be substantially improved in the 2nd half compared to the 1st
 67 half, with a large effect. The equivalent comparisons for the
 68 no-interpenetration feedback, visual interpenetration, and com-
 69 bined interpenetration feedback were not statistically signifi-
 70 cant. Importantly, the size of change for electrotactile interpe-
 71 netration feedback from the 1st to the 2nd half was significantly
 72 larger than the size of change of the no-interpenetration feed-
 73 back ($g = 0.54$, $p = .027$) and visual interpenetration feed-
 74 back ($g = 0.59$, $p = .012$), with a moderate effect size in both
 75 comparisons.
 76

4.2.2. Calibration of electrotactile feedback

77 The pairwise comparisons are displayed in Figure 7. The
 78 sensation threshold (i.e., the intensity that the participant com-
 79 mences perceiving the electrotactile feedback), the discomfort
 80

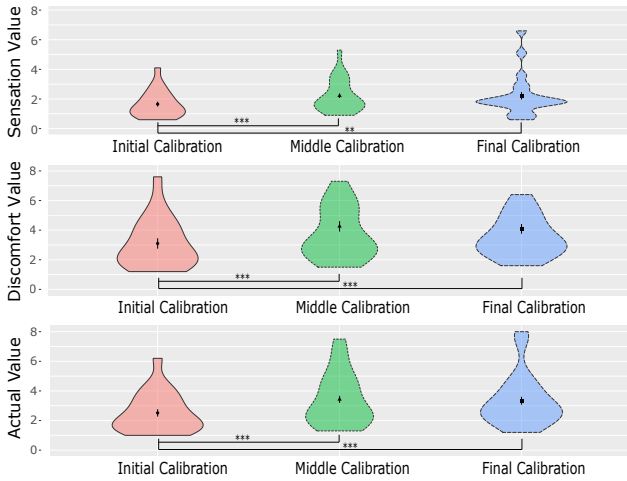


Fig. 7. Intensity values in mA. Comparisons for each calibration.

threshold (i.e., intensity that the participant commences feeling discomfort due to electro-tactile feedback), and the actual value (i.e., the weighted intensity that was implemented to provide electro-tactile interpenetration feedback) of the middle (i.e., after the 1st and before the 2nd half of experiment) and final calibration (i.e., after the 2nd half of experiment) were statistically greater than the equivalent intensities of initial calibration (i.e., before the 1st half of experiment). Specifically, the sensation threshold ($g = 1.45, p < .001$), the discomfort threshold ($g = 0.91, p < .001$), and the actual value ($g = 1.08, p < .001$) of middle calibration were substantially larger than the equivalent intensities of initial calibration, while the effect size was large to very large in each comparison. Similarly, the sensation threshold ($g = 0.70, p = .005$), the discomfort threshold ($g = 0.83, p < .001$), and the actual value ($g = 0.88, p < .001$) of final calibration were significantly larger than the equivalent intensities of initial calibration, while the effect size was large in every comparison. However, no significant differences were detected between final and middle calibration, which postulates the rejection of **H5** (sensation and discomfort thresholds will increase monotonically during the experiment). Finally, none of the intensity values was significantly correlated either positively or negatively with any of the performance variables.

4.2.3. Subjective results

The descriptive statistics of the post-exposure self-reports are displayed in Table 1, which support **H6** (electro-tactile feedback will be reported useful and coherent). In support of **H7**, the Wilcoxon signed rank test yielded no significant differences in the comparisons between the visual and electro-tactile interpenetration feedback pertaining to usefulness (i.e., how useful was the feedback for the task's completion), coherence (i.e., how much coherent was the feedback with touching the surface), and resemblance (i.e., how much the feedback resembles touching a real surface). The Wilcoxon rank sum test, for the question pertaining to the combined feedback condition, indicated a significant difference $p = .024$ between electro-tactile and combined feedback, postulating that the participants reported that they relied significantly more on the electro-tactile interpenetration feedback rather than both interpenetration feedbacks (i.e.,

visual and electro-tactile). However, in the same question, there was no significant difference between visual and electro-tactile interpenetration feedback suggesting a balanced preference.

Table 1. Self-reports on Electro-tactile Interpenetration Feedback.

Criterion	Median	Mode	Range
Usefulness	6	5	2 - 7
Coherence	5	5	4 - 7
Resemblance	2.5	1	1 - 6
Pleasantness	4	4	3 - 6
Perceptual Update	5.5	6	2 - 7
Combined Synchronicity	6	7	2 - 7

$N = 21$; $Max = 7$; ≥ 4 indicate positive response;
 Median = middle number of the provided responses;
 Mode = most frequent response

Moreover, the participants reported that the visual interpenetration feedback was useful and coherent, albeit that provided a feeling that is different from touching a real surface. Similarly, it was reported that the electro-tactile interpenetration feedback was useful to very useful and coherent, albeit that provided a feeling that is different to very different from touching a real surface. Also, the self-reports suggested that the electro-tactile interpenetration feedback provided neither a pleasant nor unpleasant sensation, as well as that it provided a frequent to very frequent perceptual update of pressing down the surface. Finally, the self-reports indicated that the combination of electro-tactile and visual interpenetration feedback had a very coherent to completely coherent synchronization, and it was perceived as moderately similar as to touching a real surface.

4.3. Discussion

Our findings agree with previous studies, where bimodal feedback increased the accuracy and precision in contact tasks [3]. Also, our results are in accordance with a meta-analysis of user interaction studies, where the bimodal (i.e., visuohaptic) feedback was found to improve performance [50]. However, a haptic uncanny effect may substantially compromise the benefits of bimodal feedback on performance [48]. In our study, the dynamic visual interpenetration feedback was matched to the varying intensities of electro-tactile interpenetration feedback, which aligns with the suggestions to mitigate or evade a haptic uncanny effect [48]. Hence, our results further support the importance of having matched feedback modalities, when implementing bimodal feedback.

Furthermore, our quantitative and qualitative outcomes align with the qualitative results of Pamungkas, et al. [51], where participants reported that the electro-tactile interpenetration feedback assisted them with performing a VR robot-teleoperation task faster and more accurately. However, in our quantitative user study the benefits of providing electro-tactile interpenetration feedback became apparent only in the 2nd half of experiment, suggesting the presence of a learning effect. Also, the intensity values for providing electro-tactile interpenetration feedback were substantially increased in the middle calibration, which were used in the 2nd half of experiment. In conjunction, our findings postulate that the advantages of electro-tactile interpenetration feedback may surface, when the user

has been familiarized with it, and/or the intensity of feedback is well-adjusted to skin's conductivity changes and/or user's increased tolerance to the electrotactile interpenetration feedback. However, the intensity values were not correlated with neither accuracy nor precision. Thus, the increased familiarity with the electrotactile interpenetration feedback that was inferred due to the observed learning effect, appears to better explain why the advantageous effects of electrotactile interpenetration feedback on performance were surfaced only during the 2nd half of experiment.

It should be noted that the learning effect was not generally present. The learning effect was identified only for the bimodal visuotactile feedback regarding accuracy, as well as for the electrotactile interpenetration feedback regarding both accuracy and precision. These findings indicate that the learning effect was important only in conditions where the electrotactile interpenetration feedback was used. Also, the size of the improvement in the accuracy and precision from the 1st to the 2nd half of experiment was significantly greater for the electrotactile interpenetration feedback condition compared to the size of improvement for no-interpenetration feedback and visual interpenetration feedback conditions respectively. This finding also postulates that the learning effect was observed due to the novelty of the electrotactile interpenetration feedback, and not due to a practice effect related to the task. Nevertheless, the effects of the familiarity with electrotactile interpenetration feedback and the refined calibration on user's performance should be further scrutinized in prospective studies.

Finally, the results postulate the effectiveness of electrotactile and/or visual interpenetration feedback. However, the implemented visual interpenetration feedback requires constant visual focus, it could occlude other visual information, and it renders visual artifacts in a fully interactive virtual environment, which may reduce substantially the contact precision and accuracy. As an example, Qian et al. [52] proposed a VR training laparoscopic surgery simulator, where rendering of visual artifacts would decrease the reality of the simulator and would interfere with the visualization of the internal organs. In contrast, the suggested electrotactile interpenetration feedback appears to facilitate multiple contact interactions, although this should be further examined. Thus, the presented electrotactile feedback system seems to be the most appropriate and effective choice for improving precision and accuracy of mid-air interactions in immersive VR. These findings can be applied in similar fields such as in tele-operation and for different interactions such as grasping, or finger sliding as the feedback enables precise contact while also providing in real-time rich tactile information.

As future work, it would be interesting to compare the precision and accuracy achieved when using a different type of tactile feedback such as finger pressure or vibrotactile feedback. For the particular case of vibrotactile feedback, based on the outcomes presented in [53], vibrotactile feedback does not seem to improve performance as electrotactile does in a Fitts's Law selection task.

Nevertheless, as discussed above, the recurrent calibration, for adjusting the electrotactile feedback's parameters to the users' preferences, appears to play a central role for improv-

ing users' performance. Currently, there is not a calibration process that can be performed independently (i.e., by the users themselves) while the users are immersed in the virtual environment. In this paper, we therefore propose a calibration system that is embedded in the virtual environment.

5. Calibration experiment

In the literature (see [54]), and as reviewed in Section 2.2, there are a number of works that focused on the improvement of the calibration of electrotactile feedback. However, these methods still require manual adjustment of the intensity values in order to achieve an optimal user experience. For example, a number of electrical stimulators measure the impedance of the skin in order to render a constant sensation, yet, users' optimal sensation level still requires to be calibrated [54]. Other methods consider previously measured data to create an initial rough calibration by extrapolation, yet, these values might require further refinement to achieve optimal calibration values. In overall, these methods follow strict rules, such as staircase method, where each sensation value is played for fixed amount of time, in which the user have a minimal control during the calibration. In any case, the calibration must be validated by the user and that could become a tedious and time consuming procedure.

The previous experiment highlighted that calibration is a critical part of the rendering of tactile sensations using electrotactile feedback and multiple calibrations might be needed to account for the participant's adaptation to the stimulation. Thus, we decided to explore alternative ways to calibrate the system. In an ideal calibration procedure, the user should be autonomous while performing the calibration without the need of external support (e.g. experimenter). More importantly, the calibration system needs to follow a number of safety rules in order to not let the user set unpleasant values by mistake. Furthermore, as the quality of the sensation depends on the contact between the electrode and the skin, the input mechanism used by the user should not interfere with it. For example, traditional input methods (mouse/keyboard/controllers) are designed to be used with the dominant hand which is also the target for rendering tactile sensations. Based on this, mid-air interactions could be of benefit for interacting with a calibration system when the dominant hand is cluttered with the VR and electrotactile equipment (e.g. stimulator, electrodes, trackers). Moreover the contact between the electrode and the skin should not be altered by a physical contact with the worn equipment. Finally, the system should provide a fast but accurate calibration procedure, which can be performed recurrently while the user is immersed in the virtual environment.

5.1. Calibration in VR using mid-air interaction

Based on the lessons learned from our first experiment [55], we proposed an interactive method to calibrate the intensity of the electrical stimulation. In this method, we considered a mid-air interaction technique in which the users could use their virtual hand representation (index finger) to interact with a 3D slider to adjust the intensity of the feedback.



Fig. 8. Interface of the calibration experiment with participant adjusting the intensity using its index finger to drag a 3D slider in VR.

Using this technique, participants can calibrate the intensity of the feedback while wearing a VR HMD. Participants use their virtual index finger to decrease or increase the intensity by dragging the highlighted part of a virtual slider left and right. The slider has a total length of 1.76 m and consists of 88 slices (2 cm each), allowing exploring the full length from a seated position, and is located in front of the user (see Figure 8). The stimulation is only enabled when the finger of the participant is inside the virtual slider. The range of intensities goes from 0.2 mA to 9.0 mA, making the resolution of the slider match the resolution of the stimulator that we used (increments of 0.1 mA). Furthermore, to avoid sudden/unwanted changes on the value of the slider, the slider only changes by activating consecutive slices, i.e. participants need to drag the last active slice, so that they can not set a high value by mistake. This design avoided users making fast/unwanted motions that could increase the intensity of the stimulation beyond their discomfort threshold. This is an important aspect, as it ensures a safe calibration and subsequent safe electro-tactile interaction.

5.2. Evaluation

This section describes a user study evaluating the proposed calibration method (3D slider in VR) against a baseline in which participants used a desktop-based method using a traditional physical keyboard.

5.2.1. Calibration using traditional keyboard

In the keyboard method, participants looked at a regular monitor displaying a fixed point of view of the scene with the slider at the center of the screen (see Figure 9). Participants could use the keyboard to interact with the virtual slider. Pressing the left/right arrows of the numeric keyboard to decrease/increase the intensity (which will also turn the stimulation on), pressing the delete key of the numeric keyboard to stop the stimulation and pressing the insert key of the numeric keyboard to toggle the sensation on/off.

The keyboard interaction was mapped to the visual slider, so each key-press event activated the immediate consecutive slice. To make the slider advance farther, multiple key-presses were needed instead of going all the way up with a single long key-press.

In order to provide consistent feedback for both methods, when the stimulation was off, the slider had a gray color



Fig. 9. Desktop-based calibration process using a keyboard. Participant needs to temporarily lift the HMD to look at the monitor.

whereas when is on, the slider glowed with a light blue or an orange color based whether the participant was calibrating the sensation or discomfort threshold. For both conditions, the calibration of the discomfort threshold was performed from the previous value set as sensation rather than starting from zero.

5.2.2. Participants and apparatus

A total of 16 individuals [age: mean(SD) = 27.3(7.3); range = 22 – 52 years old; gender: 8 males; 8 females] were recruited through an in-campus advertisement. All 16 participants were familiar with using VR HMDs, 12 had previous experience with tactile devices and 7 had previous experience with electro-tactile feedback.

The equipment was the same as the one used in previous experiment. The calibration was performed only for the central pad placed at the center of the finger pad with a fixed pulse width of 150 μ s and a frequency of 200 Hz.

5.2.3. Experimental protocol

At the beginning of the experiment, participants were informed about the nature of the experiment and were asked to read and sign the informed consent form. After that, participants answered a pre-questionnaire where they answered some demographic questions followed by questions assessing their experience with VR, haptics and electro-tactile equipment. Then, we asked the participants to determine the sensation and discomfort thresholds using both methods. Both shared the same visual feedback which consisted of a 3D slider and a black board for providing written instructions (see Figure 8). The order of the calibration method was counterbalanced. Moreover, to test for potential learning effects, the calibration procedure was performed twice. For example, participants performed the calibration first with the keyboard method, then with the VR method, and then repeated again. Participants performed the calibration twice for each method. Before performing the calibration, participants had time to get familiarized with both interaction methods (in the same order as in the experiment). During this familiarization process, no tactile sensation was rendered so they could focus only on the interaction.

Once the main task was over, participants answered a SUS-like questionnaire evaluating the usability of each interaction method.

5.2.4. Dependent variables and hypotheses

Based on our hypotheses and the experimental task we measured the following metrics within each trial: sensation threshold, discomfort threshold, sensation dynamic range, intensity adjustments and calibration time. The sensation and discomfort thresholds were set directly by the participants using one of the calibration methods. The sensation dynamic range was calculated as the difference between the discomfort and the sensation thresholds. The intensity adjustments considered the amount of times that the intensity was updated. For each condition the intensity updates were discrete, either pressing a key or dragging the slider directly. The calibration time was measured starting at the first time the participant interacted with the system during the trial until the time when they finalised the calibration. Sensation, discomfort and dynamic range are measured in milliamperes whereas the calibration time is measured in seconds.

At the end of the experiment, participants answered a modified version of the SUS questionnaire (see Table 2) composed of eight paired questions per condition, using a 5-Likert scale: *Strongly Disagree, Disagree, Neither, Agree, Strongly Agree*. The first six questions [Q1-Q6] were taken from the original SUS questionnaire which were applicable for our system comparison and the last two [Q7, Q8] were added with the intention to corroborate objective metrics with participants' perception.

In this respect our hypotheses were:

- **[H1]** When using the slider in VR as interaction method, the calibration time will decrease. Also, the calibration time will decrease as the experiment advances.
- **[H2]** The interaction method will not have an effect on the perceived intensity, producing similar sensation and discomfort thresholds under any interaction condition.
- **[H3]** The VR slider calibration method will increase the interaction in terms of number of intensity adjustments. Also, the number of adjustments will decrease as the experiment advances.

5.3. Results

The homogeneity and normality assumptions were assessed. The discomfort, dynamic range, and duration of the calibrations violated the normality assumption. The distributions were positively skewed. The values were then transformed using a logarithmic transformation. No further violations were detected after the logarithmic transformation of the data.

A two-way repeated measures ANOVA was performed for each continuous variable. The sphericity assumption was never violated in the ANOVA analyses. The ANOVA analyses were followed by post-hoc pairwise comparisons. Lastly, the participants' self-reports on each calibration system's usability (i.e., modified SUS questionnaire) were examined. Non-parametric pairwise comparisons were performed to scrutinize the reported usability aspects.

5.3.1. Calibration duration

In line with **H1**, the results of the ANOVA analysis revealed significant main effects for both calibration type and calibration's repetition. However, there was not a significant interaction effect between calibration type and calibration's repetition.

The calibration type had a main effect of ($F(1, 14) = 13.89, p = .002$) indicating significant differences between the calibration types. The calibration type had a large effect size of ($\omega^2 = 0.11, 95\% CI[0, 1]$) on the duration of calibration. Comparably, the calibration's repetition had a main effect of ($F(1, 14) = 34.61, p < .001$) suggesting a substantial difference between the 1st and the 2nd repetition. The produced effect size was of ($\omega^2 = 0.14, 95\% CI[0, 1]$) indicating a large effect of the repetition on the calibration's duration.

The post-hoc pairwise comparison are illustrated in Figure 10. The results strongly support both aspects of **H1**. The VR slider calibration method was substantially faster than the keyboard method, and the difference between them was of a large effect size of ($g = 0.61, p = .002$). Similarly, the duration of the 2nd repetition, regardless of the calibration type, was significantly shorter than the 1st repetition, and the effect size was equally large ($g = 0.78, p = .001$).

5.3.2. Perceived intensity and thresholds

The ANOVA analyses for the sensation and discomfort thresholds, respectively, did not indicate any significant main effect of the calibration type on the sensation and discomfort thresholds. These results align with the **H2**. However, a significant main effect ($F(1, 15) = 15.59, p = .002$) on sensation's threshold was identified due to the calibration's repetition. Nevertheless, the effect size of the calibration's repetition on the sensation threshold ($\omega^2 = -0.001, 95\% CI[0, 1]$) was extremely small. Similarly, the non-significant effect size ($\omega^2 = -0.001, 95\% CI[0, 1]$) of calibration's repetition on discomfort threshold was equally small. Also, there was not any significant interaction effect for both thresholds. Finally, none significant main or interaction effect of calibration type and/or repetition on the dynamic range of electrotactile feedback was detected.

The post-hoc comparisons between 1st and 2nd repetition are displayed at Figure 11. The sensation threshold in the 1st repetition was substantially smaller compared to the 2nd one, and the effect size was large ($g = -0.86, p < .001$). Also, a small size effect ($g = -0.20, p = .270$) was seen in discomfort threshold, albeit the difference was not significant. Finally, as seen in Figure 11, compared to the sensation threshold, the distribution

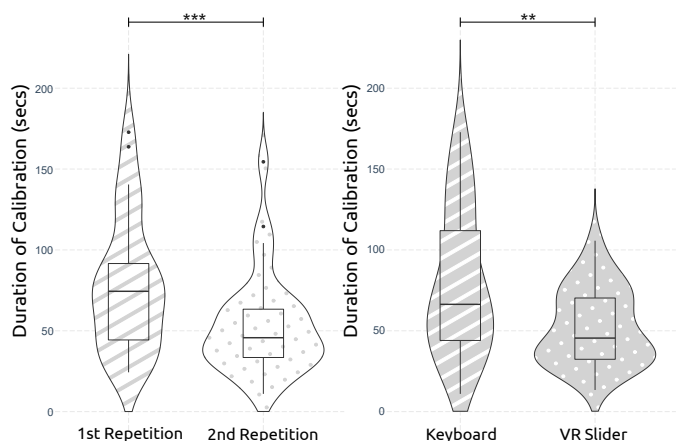


Fig. 10. Duration of Calibration Process in secs. Comparisons between Repetitions (Left) and Calibration Types (Right).

Table 2. Usability questionnaire administered. The last columns present the obtained results for each condition (Median [IQ1-IQ3]).

ID	Question	Keyboard Scores	VR Scores
Q1 - Complexity	I found that the calibration procedure was unnecessarily complex.	3.5 [3-4]	4 [3-4]
Q2 - Easiness	I thought the calibration system was easy to use.	3 [3-4]	4 [3-4]
Q3 - Fast Learning	I would imagine that most people would learn to use this calibration system very quickly.	4 [3-4]	4 [3.75-4]
Q4 - Cumbersomeness	I found that the calibration procedure was very cumbersome.	3 [2.75-4]	4 [3-4]
Q5 - Confidence Level	I felt very confident while using the calibration system.	3 [3-4]	3 [3-4]
Q6 - Learning Curve	I needed to learn a lot of things regarding the method before I could do the calibration properly.	4 [3-4]	4 [3-4]
Q7 - Speed*	The calibration system allowed me to perform the calibration fast.	3 [3-3.25]	4 [3-4]
Q8 - Precision	The calibration system allowed me to perform the calibration accurately.	4 [3-4]	3 [3-4]

*Significant difference. VR faster than Keyboard ($p < 0.01$)

of discomfort threshold was wider, and the mean values much higher.

5.3.3. Thresholds adjustments

Regarding the number of adjustments of each threshold during the calibration process, the ANOVA analyses detected significant main effects of the calibration type on the adjustments of both thresholds. These main effects are in support of **H3**. Specifically, the calibration type had a significant main effect ($F(1, 15) = 14.29, p = .002$) on the number of adjustments of sensation's threshold. The calibration type had a moderate to large effect size of ($\omega^2 = 0.08, 95\% CI[0, 1]$) on the adjustments of sensation's threshold. Comparably, calibration type had also a significant main effect ($F(1, 15) = 7.84, p = .014$) on the number of adjustments of discomfort's threshold. However, in this case, the effect size was small to moderate ($\omega^2 = 0.02, 95\% CI[0, 1]$).

The post-hoc comparisons for the number of adjustments of sensation and discomfort threshold respectively are displayed at Figure 12. Compared to the keyboard calibration system, the users explored substantially more intensity values for identifying their sensation threshold while using the VR slider calibration system, and the effect size of this difference was of medium size ($g = -0.48, p = .001$). Likewise, the users explored significantly more intensity values for identifying their discomfort

threshold while using the VR slider calibration system. Equally, the effect size of this difference was of medium size ($g = -0.47, p = .010$). Finally, regardless the calibration type, compared to the 1st repetition, the users explored less values for identifying their discomfort threshold in the 2nd repetition, and the effect size of this difference was moderate ($g = -0.42, p = .020$). These results are in line with the **H3**.

5.3.4. SUS questionnaire

The descriptive statistics of the questionnaire are shown in Table 2. The VR interaction got a score of 87.5 ± 10.94 while the score for the keyboard was of 82.62 ± 14.66 (max achievable score is 100). We analyzed the difference between the scores using a two-sample Wilcoxon-test and this yielded no significant difference. Then we explored potential differences within questions using again a two-sample Wilcoxon-test. No significant differences were detected, except for *Q7* regarding the speed of performing the calibration process. Based on these self-reports, the VR slider was rated as substantially faster ($p = .005$) than the keyboard-based calibration. This result further supports **H1**.

5.4. Discussion

In overall, the results are in accordance with our hypotheses. First, the objective and subjective results for the duration of cal-

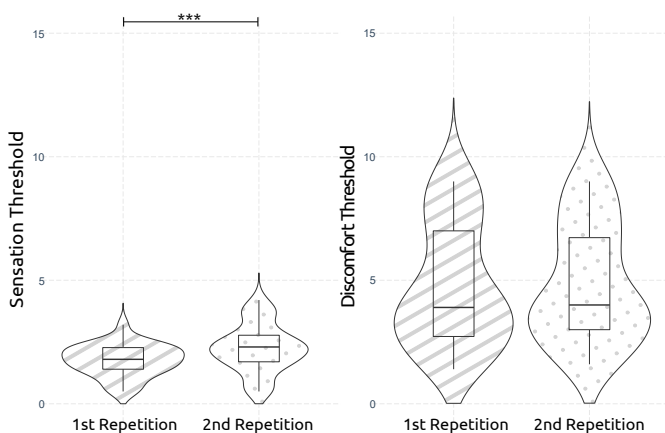


Fig. 11. Sensation (Left) and Discomfort (Right) Thresholds. Comparisons between Repetitions.

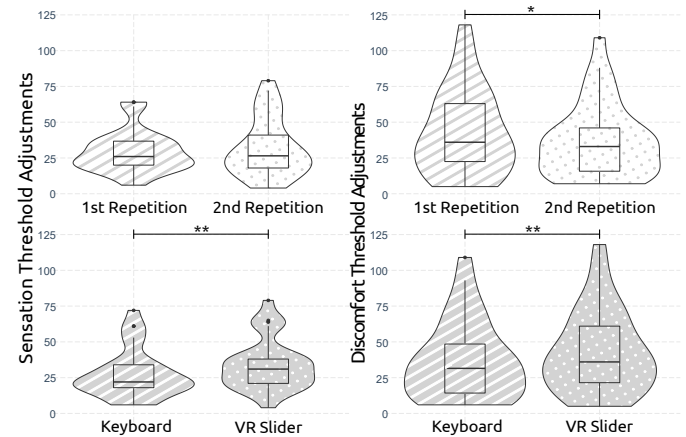


Fig. 12. Number of Adjustments of Sensation (Left) and Discomfort (Right) Thresholds. Comparisons between Repetitions (Top) and Calibration Types (Bottom).

ibration process agree with **H1**, i.e. participants performed the calibration significantly faster when using the VR interaction than when using the keyboard and this was actually perceived by them and reflected on their self-reports. These results were expected because we enforced multiple *key-presses* rather than a *press and hold* keyboard interaction for increasing the intensity. This imposition was added in order to provide a safe calibration procedure and this has also its counter-part in the VR condition where intensity increments need to be performed by activating slice by slice. Moreover, we found a reduction in the calibration time during the second repetition which turned out to be independent of the calibration method, i.e. participants performed the calibration faster during the second repetition (learning effect) but keeping the relative speed between the two calibration methods. This learning effect was expected for two reasons. Firstly, they knew by then how to perform the tasks more efficiently. Secondly, they had already figured out what were their sensation and discomfort thresholds from the previous iteration.

Regarding **H2**, the results confirmed that the calibration method would not have an impact on the calibration thresholds. Participants managed to set the same values regardless of the interaction. We recall that both methods have the same resolution of 0.1 mA and it seems that the physical size chosen for the individual slices (2 cm), proposed no problem for the participants when it comes to precisely select them. The significant difference of sensation threshold between calibration's repetition agreed with the finding of our previous experiment, where participants required a higher intensity value in the second calibration to perceive the electrical stimulation. We suggest as one of the reasons the familiarization with the stimuli but this needs to be further examined. The fact that the difference was significant only for the sensation threshold and not for the discomfort could be due to the expected variance of both thresholds. In general, both thresholds increased during the second repetition but these increments were compared to the each variances. Participants answered less accurately whether a particular intensity value was uncomfortable or not; not so much being the case for the binary question whether they felt something or not.

Finally, our results surfaced an interesting difference between the two calibration methods regarding the number of adjustments. In line with **H3**, the results showed that the participants, while using the VR method, explored more intensity values (i.e., number of adjustments) in order to select their sensation and discomfort thresholds. Nonetheless, the VR calibration method was also performed faster by the participants. This leads us to the conclusion that participants were exposed to a higher number of values in a shorter period of time which benefits calibration's efficiency. The results also confirmed that there is a decrease of number of adjustments during the second repetition, which we associate with a learning effect for similar reasons to **H1**. The participants had thus improved in performing the calibration, while they had previously identified the threshold that should strive to reach.

We should recall that in this experiment, all 16 participants had prior experience with VR technology, which might have had an effect on their performance as they were familiarized with the technology.

As future work, we should explore alternative mid-air interactions such as pressing virtual buttons for adjusting the intensity of the feedback and evaluate if the speed of the calibration is comparable to the speed of using the virtual 3D slider.

6. General Discussion

Haptic devices provide sensations and information crucial to both presence and performance in VR [7, 54, 56]. However, the wearability of haptic devices is a key component for their effective implementation in VR [7, 56]. Electrotactile devices appear promising for offering rich tactile sensations and an adequate wearability [54]. In the 1st experiment, our findings agree with previous studies (e.g., [11, 9]), where the electrotactile feedback brought performance related benefits. However, as discussed above, the recurrent calibration of the intensity is a key issue for implementing electrotactile feedback in VR. In the 2nd experiment, we delivered a calibration system in VR, which was efficient, ergonomic, and fast. These outcomes further pave the way for the implementation of electrotactile feedback in VR.

Specifically, in the 1st experiment, we saw that the performance benefits surfaced in the 2nd half, after the 2nd calibration. This was attributed to the familiarization of the participants to the electrotactile feedback and/or the corrective effect of the 2nd calibration to provide the users with more appropriate electrotactile feedback's intensity. While in the 1st experiment, both sensation and discomfort thresholds were substantially increased, in the 2nd experiment only the sensation threshold was increased. This can be attributed to the prolonged exposure of participants to the electrotactile feedback between the first two calibrations of the 1st experiment. In contrast, the participants in the 2nd experiment, went only through a calibration process by using the other calibration method between the two calibration's repetitions (e.g., 1st VR slider - 1st Keyboard - 2nd VR slider). Thus, the continuous exposure may have influenced the increased values between the first two calibrations of the 1st experiment.

However, in the 2nd experiment, both thresholds were indeed increased, albeit that only sensation threshold's increase was significant. Nevertheless, the effect size of the calibration's repetition on the sensation threshold was substantially small. Hence, indeed, both thresholds in the 2nd experiment were not affected by the calibration's repetition, in contrast with the 1st experiment, where the effect size of calibration's iteration on the thresholds was large. However, when comparing qualitatively the results of the 1st and 2nd experiment, we observed certain similarities. When considering the 3rd calibration in the 1st experiment and the mean values of the 2nd repetition in the 2nd experiment, we observed comparable results. Sensation thresholds for both cases had mean values of 2.2 mA while the mean discomfort thresholds were higher (4.2 mA for the first, and 4.9 mA for the second).

Considering that length of both experiments and the time participants were exposed to electrotactile feedback, these results seems to suggest that once the participants were used to the calibration procedure, they were able to consistently calibrate the system. For example, for the first calibration of the 1st experiment, participants were not always able to obtain optimal

calibration parameters, while this was the case even for the 1st repetition of the 2nd experiment.

7. Conclusion

In this paper, we proposed an electrotactile rendering algorithm to enhance contact information in a virtual environment based on the modulation of the pulse width and frequency of the electrical signal and explored alternative ways to improve the calibration procedure of the electrotactile feedback which was found key for the optimal perception of the tactile sensations. In order to explore the benefits and limitations of the interpenetration feedback method, we first conducted a user study evaluating the performance in touching accurately and precisely virtual rigid objects with various interpenetration feedback. The results showed that participants achieved significantly better performance in terms of accuracy and precision when visual and/or electrotactile interpenetration feedback was provided. More importantly, there were no significant differences between visual and electrotactile interpenetration feedback when the proper intensity was used and once the user was familiarized with the sensation of electrotactile feedback. Considering that visual discrimination is dominant in such scenarios and a visual interpenetration feedback renders visual artifacts, the findings indicate a promising future for electrotactile-based systems for improving contact precision and accuracy in interactive VR systems.

In the second user study, we explored how the calibration procedure for electrotactile feedback could be improved and integrated directly within the virtual environment. The results showed that users were able to perform faster calibrations with a comparable accuracy using the VR calibration method.

Taken together, the reported results showed the potential of wearable electrotactile devices for eliciting tactile sensations in a virtual reality context. Nevertheless there are still a number of future works that are still required. For example, there is the need to explore other alternatives for the modulation and location of the electrotactile feedback or consider other tactile actuators. In addition, in our experiment, the user could not interact freely with his/her fingers as we asked them to keep a fixed hand pose, which could potentially modulate the tactile perception. More complex interactions such as grasping or interactions with dynamic objects (e.g. pushing a virtual object) need to be explored. Finally, the calibration of systems with a higher number of pads still remains an open research question.

Acknowledgments

This work was supported by the European Union's Horizon 2020 research and innovation program under grant agreement No. 856718 (TACTILITY).

References

[1] Carruth, DW. Virtual reality for education and workforce training. In: 2017 15th International Conf. Emerging eLearning Technologies and Applications (ICETA). 2017, p. 1–6.
 [2] Jensen, L, Konradsen, F. A review of the use of virtual reality head-mounted displays in education and training. *Education and Information Technologies* 2018;23(4):1515–1529.

[3] Triantafyllidis, E, McGreavy, C, Gu, J, Li, Z. Study of multi-modal interfaces and the improvements on teleoperation. *IEEE Access* 2020;8:78213–78227.
 [4] Zilles, CB, Salisbury, JK. A constraint-based god-object method for haptic display. In: *Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots*; vol. 3. IEEE; 1995, p. 146–151.
 [5] Sagardia, M, Hulin, T. A fast and robust six-dof god object heuristic for haptic rendering of complex models with friction. In: *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology. VRST '16*; Association for Computing Machinery; 2016, p. 163–172.
 [6] Prachyabrued, M, Borst, CW. Design and Evaluation of Visual Interpenetration Cues in Virtual Grasping. *IEEE Trans Visualization and Computer Graphics* 2016;22(6):1718–1731.
 [7] Pacchierotti, C, Sinclair, S, Solazzi, M, Frisoli, A, Hayward, V, Prattichizzo, D. Wearable haptic systems for the fingertip and the hand: Taxonomy, review, and perspectives. *IEEE Trans Haptics* 2017;10(4):580–600.
 [8] Chouvardas, V, Miliou, A, Hatalis, M. Tactile displays: Overview and recent advances. *Displays* 2008;29(3):185–194.
 [9] Pamungkas, DS, Ward, K. Electro-tactile feedback system to enhance virtual reality experience. *International Journal of Computer Theory and Engineering* 2016;8(6):465–470.
 [10] Yem, V, Kajimoto, H. Wearable tactile device using mechanical and electrical stimulation for fingertip interaction with virtual world. In: *IEEE Virtual Reality (VR)*. 2017, p. 99–104.
 [11] Hummel, J, Dodiya, J, Center, GA, Eckardt, L, Wolff, R, Gerndt, A, et al. A lightweight electrotactile feedback device for grasp improvement in immersive virtual environments. In: *Proc. of IEEE Conf. Virtual Reality*. 2016, p. 39–48.
 [12] Kaczmarek, K, Webster, J, Bach-y Rita, P, Tompkins, W. Electrotactile and vibrotactile displays for sensory substitution systems. *IEEE Transactions on Biomedical Engineering* 1991;38(1):1–16.
 [13] Stephens-Fripp, B, Alici, G, Mutlu, R. A review of non-invasive sensory feedback methods for transradial prosthetic hands. *IEEE Access* 2018;6:6878–6899.
 [14] Frisoli, A, Solazzi, M, Salsedo, F, Bergamasco, M. A fingertip haptic display for improving curvature discrimination. *Presence: Teleoperators and Virtual Environments* 2008;17(6):550–561.
 [15] Gabardi, M, Solazzi, M, Leonardis, D, Frisoli, A. A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features. In: *Proc. IEEE Haptics Symposium*. 2016, p. 140–146.
 [16] Minamizawa, K, Kajimoto, H, Kawakami, N, Tachi, S. A wearable haptic display to present the gravity sensation-preliminary observations and device design. In: *Proc. World Haptics*. 2007, p. 133–138.
 [17] Prattichizzo, D, Chinello, F, Pacchierotti, C, Minamizawa, K. Remotouch: A system for remote touch experience. In: *19th International Symposium in Robot and Human Interactive Communication*. 2010, p. 676–679.
 [18] Pacchierotti, C, Salviotti, G, Hussain, I, Meli, L, Prattichizzo, D. The hRing: a wearable haptic device to avoid occlusions in hand tracking. In: *Proc. IEEE Haptics Symposium*. 2016.
 [19] Aggravi, M, Pausé, F, Giordano, PR, Pacchierotti, C. Design and evaluation of a wearable haptic device for skin stretch, pressure, and vibrotactile stimuli. *IEEE Robotics and Automation Letters* 2018;3(3):2166–2173.
 [20] Salazar, SV, Pacchierotti, C, de Tinguy, X, Maciel, A, Marchal, M. Altering the stiffness, friction, and shape perception of tangible objects in virtual reality using wearable haptics. *IEEE Trans Haptics* 2020;13(1):167–174.
 [21] De Tinguy, X, Pacchierotti, C, Marchal, M, Lécuyer, A. Enhancing the stiffness perception of tangible objects in mixed reality using wearable haptics. In: *Proc. of IEEE Conf. Virtual Reality and 3D User Interfaces*. 2018, p. 81–90.
 [22] Gosselin, F, Chabrier, A, Weistroffer, V, Girard, A. Design and development of miniature wearable haptic interfaces for the fingertips. In: *Proc. of IEEE World Haptics Conference*. 2017, p. 611–616.
 [23] Jorgovanovic, N, Dosen, S, Djovic, DJ, Krajoski, G, Farina, D. Virtual grasping: closed-loop force control using electrotactile feedback. *Computational and mathematical methods in medicine* 2014;2014.
 [24] Sato, K, Kajimoto, H, Kawakami, N, Tachi, S. Electrotactile display for integration with kinesthetic display. In: *RO-MAN 2007-The 16th IEEE International Symposium on Robot and Human Interactive Communication*. IEEE; 2007, p. 3–8.

- [25] Yem, V, Vu, K, Kon, Y, Kajimoto, H. Effect of Electrical Stimulation Haptic Feedback on Perceptions of Softness-Hardness and Stickiness while Touching a Virtual Object. In: Proc. of IEEE Conf. Virtual Reality and 3D User Interfaces. 2018, p. 89–96.
- [26] Gregory, J, Xi, N, Shen, Y. Towards on-line fingertip bio-impedance identification for enhancement of electro-tactile rendering. In: 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems. 2009, p. 3685–3690.
- [27] Fadali, MS, Shen, Y, Jafarzadeh, S, Yi, J. Electro-tactile preference identification using fuzzy logic. In: 2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society. 2009, p. 1585–1588.
- [28] Kajimoto, H. Electrotactile display with real-time impedance feedback using pulse width modulation. *IEEE Transactions on Haptics* 2012;5(2):184–188.
- [29] Akhtar, A, Boyce, B, Bretl, T. The relationship between energy, phase charge, impedance, and perceived sensation in electrotactile stimulation. In: IEEE Haptics Symposium, HAPTICS. 2014, p. 69–74.
- [30] Akhtar, A, Sombek, J, Boyce, B, Bretl, T. Controlling sensation intensity for electrotactile stimulation in human-machine interfaces. *Science robotics* 2018;3(17).
- [31] Rahimi, M, Jiang, F, Shen, Y. Non-Linearity of Skin Properties in Electrotactile Applications: Identification and Mitigation. *IEEE Access* 2019;7:169844–169852.
- [32] Rahimi, M, Shen, Y. Adaptive spatial mapping of electro-tactile threshold based on subdivision bio-impedance feedback. In: IEEE International Conference on Real-Time Computing and Robotics, RCAR; vol. 2019-Augus. 2019, p. 164–169.
- [33] Isakovic, M, Malešević, J, Keller, T, Kostić, M, Štrbac, M. Optimization of Semiautomated Calibration Algorithm of Multichannel Electrotactile Feedback for Myoelectric Hand Prosthesis. *Applied Bionics and Biomechanics* 2019;2019.
- [34] de Tinguy, X, Howard, T, Pacchierotti, C, Marchal, M, Lécuyer, A. Weatavix: Wearable actuated tangibles for virtual reality experiences. In: Haptics: Science, Technology, Applications: 12th International Conference, EuroHaptics 2020, Leiden, The Netherlands, September 6–9, 2020, Proceedings; vol. 12272. Springer Nature; 2020, p. 262.
- [35] Chinello, F, Pacchierotti, C, Malvezzi, M, Prattichizzo, D. A three revolute-revolute-spherical wearable fingertip cutaneous device for stiffness rendering. *IEEE Trans Haptics* 2017;11(1):39–50.
- [36] Chinello, F, Malvezzi, M, Prattichizzo, D, Pacchierotti, C. A modular wearable finger interface for cutaneous and kinesthetic interaction: control and evaluation. *IEEE Trans Industrial Electronics* 2019;67:706–716.
- [37] Young, EM, Gueorguiev, D, Kuchenbecker, KJ, Pacchierotti, C. Compensating for fingertip size to render tactile cues more accurately. *IEEE Trans Haptics* 2020;13(1):144–151.
- [38] Kuchenbecker, K, Ferguson, D, Kutzer, M, Moses, M, Okamura, A. The touch thimble: Providing fingertip contact feedback during point-force haptic interaction. In: Proc. Symposium on Haptic interfaces for virtual environment and teleoperator systems. 2008, p. 239–246.
- [39] Gonzalez, F, Bacht, W, Gosselin, F. Smooth transition-based control of encounter-type haptic devices. In: Proc. of IEEE International Conf. Robotics and Automation. 2015, p. 291–297.
- [40] Kaczmarek, KA, Tyler, ME, Okpara, UO, Haase, SJ. Interaction of Perceived Frequency and Intensity in Fingertip Electrotactile Stimulation: Dissimilarity Ratings and Multidimensional Scaling. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 2017;25(11):2067–2074.
- [41] Folgheraiter, M, Gini, G, Vercesi, D. A multi-modal haptic interface for virtual reality and robotics. *Journal of Intelligent and Robotic Systems* 2008;52(3-4):465–488.
- [42] Kajimoto, H, Kawakami, N, Maeda, T, Tachi, S. Tactile feeling display using functional electrical stimulation. In: Proc. of ICAT. 1999, p. 133.
- [43] Lozano, CA, Kaczmarek, KA, Santello, M. Electrotactile stimulation on the tongue: Intensity perception, discrimination, and cross-modality estimation. *Somatosensory & motor research* 2009;26(2-3):50–63.
- [44] Aiello, GL. Multidimensional electrocutaneous stimulation. *IEEE Trans Rehabilitation Engineering* 1998;6(1):95–101.
- [45] Varshney, LR, Sun, JZ. Why do we perceive logarithmically? *Significance* 2013;10(1):28–31.
- [46] Zhao, Y, Cutrell, E, Holz, C, Morris, MR, Ofek, E, Wilson, AD. SeeingVR: A set of tools to make virtual reality more accessible to people with low vision. In: Proc. of ACM CHI Conf. Human Factors in Computing Systems; vol. 14. 2019, p. 1–14.
- [47] Sidenmark, L, Clarke, C, Zhang, X, Phu, J, Gellersen, H. Outline Pursuits: Gaze-assisted Selection of Occluded Objects in Virtual Reality. In: Proc. of ACM CHI Conf. Human Factors in Computing Systems. 2020, p. 76–77.
- [48] Berger, CC, Gonzalez-Franco, M, Ofek, E, Hinckley, K. The uncanny valley of haptics. *Science Robotics* 2018;3(17).
- [49] Lakens, D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and anovas. *Frontiers in Psychology* 2013;4.
- [50] Burke, JL, Prewett, MS, Gray, AA, Yang, L, Stilson, FR, Coovert, MD, et al. Comparing the effects of visual-auditory and visual-tactile feedback on user performance: a meta-analysis. In: Proc. 8th international Conf. Multimodal interfaces. 2006, p. 108–117.
- [51] Pamungkas, DS, Ward, K. Tele-operation of a robot arm with electro tactile feedback. In: IEEE/ASME International Conf. Advanced Intelligent Mechatronics: Mechatronics for Human Wellbeing. 2013, p. 704–709.
- [52] Qian, K, Bai, J, Yang, X, Pan, J, Zhang, J. Virtual reality based laparoscopic surgery simulation. In: Proc. 21st ACM Symposium on Virtual Reality Software and Technology. 2015, p. 69–78.
- [53] Kourtesis, P, Vizcay, S, Marchal, M, Pacchierotti, C, Argelaguet, F. Action-specific perception & performance on a fitts’s law task in virtual reality: The role of haptic feedback. *IEEE Transactions on Visualization and Computer Graphics* 2022;.
- [54] Kourtesis, P, Argelaguet, F, Vizcay, S, Marchal, M, Pacchierotti, C. Electrotactile feedback applications for hand and arm interactions: A systematic review, meta-analysis, and future directions. *IEEE Transactions on Haptics* 2022;.
- [55] Vizcay, S, Kourtesis, P, Argelaguet, F, Pacchierotti, C, Marchal, M. Electrotactile Feedback For Enhancing Contact Information in Virtual Reality. In: Orlosky, J, Reiners, D, Weyers, B, editors. ICAT-EGVE 2021 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments. 2021, p. 103–105.
- [56] Maisto, M, Pacchierotti, C, Chinello, F, Salviotti, G, De Luca, A, Prattichizzo, D. Evaluation of wearable haptic systems for the fingers in augmented reality applications. *IEEE transactions on haptics* 2017;10(4):511–522.