Contactless Electrostatic Piloerection for Haptic Sensations

Naroa Iriarte, Iñigo Ezcurdia, Sonia Elizondo, Josu Irisarri, Daria Hemmerling, Amalia Ortiz, Asier Marzo.

***Abstract*—In this project, we create artificial piloerection using contactless electrostatics to induce tactile sensations in a contactless way. Firstly, we design various high-voltage generators and evaluate them in terms of their static charge, safety and frequency response with different electrodes as well as grounding strategies. Secondly, a psychophysics user study revealed which parts of the upper body are more sensitive to electrostatic piloerection and what adjectives are associated with them. Finally, we combine an electrostatic generator to produce artificial piloerection on the nape with a head-mounted display, this device provides an augmented virtual experience related to fear. We hope that work encourages designers to explore contactless piloerection for enhancing experiences such as music, short movies, video games, or exhibitions.**

***Index Terms*—piloerection, electrostatic, affective computing, emotion elicitation methods**

I. Introduction

With the upcoming of virtual and immersive environments, visual and auditory channels are usually complemented with tactile sensations. Haptics can increase our performance in virtual environments [47] (functional touch), our immersion [38] or affect our emotional status [2] (affective touch). Haptic gloves [35] and suits [10] based on vibration coins, micropneumatics or electrostimulation are being commercialized by several companies.

However, having to wear suits or gloves increases the setup time, is not hygienic and does not allow for the come-and-interact paradigm. Consequently, contactless solutions for haptics are being developed. The most popular is focused ultrasound [9], [17], [20], [28] which can generate soft vibrations on the palm and fingertips, the focus can be moved hundreds of times per second, enabling spatial and time-varying patterns. Air vortices [19], [43] can also produce tactile sensations but are slow and take time to arrive at the user. High-voltage sparks [44] are another alternative, but have only been tested on the fingertips and have limited reach. In general, ultrasound produces weak sensations and only on the palm and fingertips, whereas sparks and vortices provide a limited range of sensations.

M-Hair and MagHair [6], [7] applied ferromagnetic powder into the user's hairs for being able to move them with electromagnets at the other side of the forearm, it was shown that linear patterns on the hair could be differentiated. Electrostatic piloerection on the forearm has been initially explored as a contactless way to create tactile sensations [15], [16], showing that is a perceptible stimulus and that adding piloerection to an alarm sound produced a larger galvanic skin response probably due to an increase in the surprise. These initial studies suggest that a deeper analysis could expand our knowledge about electrostatic piloerection as a technology for contactless haptics.

In this project, we induce tactile sensations in a contactless way using electrostatic piloerection (Figure 1). Piloerection is an interesting trigger because: it does not leave residues in the user as liquids or aerosols may do, it can be induced in several body parts making it adaptable to desktop scenarios or head-mounted displays, it can be applied in a contactless way using electrostatics and the temporal actuation is in the order of seconds. Finally, we note that being able to stimulate hairy skin could open the door for affective touch since affective touch is connected with the C tactile afferents [31], [34], which are only present in hairy skin.

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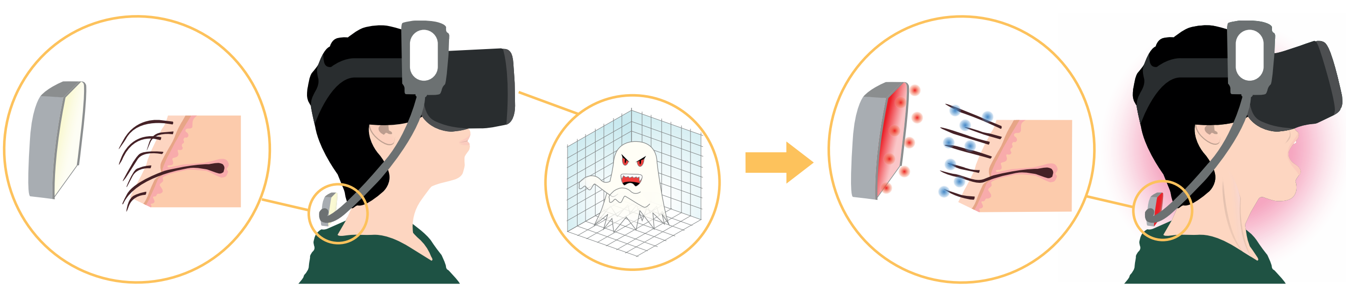

Fig. 1. The user is wearing a head-mounted display with an electrostatic generator attached, the generator is connected to an electrode above the nape. Left) The user is watching a scary clip. Right) The generator creates contactless piloerection on the hairs of the nape to affect the experience of the user. The piloerection is caused by a positive charge on the electrode, that charges the hairs negatively through induction and attracts them.

The contributions of this paper in relation to the existing research are:

- Designs of electrostatic generators and electrodes. They are characterized in terms of the induced charge on fake hairy skin and other parameters.
- A psychophysical study of the perception threshold and elicited adjectives on different body parts. The nape and wrist appear as interesting alternatives to the forearm.

In Section II, we discuss the working principle of electrostatic piloerection, design high-voltage generators, and electrodes and test their capabilities in fake hairy skin. In Section III, we conduct a psychophysical study to determine the perception thresholds and associated adjectives of the stimuli on different body parts. In Section IV, we conduct an initial pilot study using artificial piloerection on the nape combined with immersive scary clips displayed in a head-mounted display. Both user studies have been approved by the ethics and safety committee of the university (PI-025/22). Finally, in section V, we discuss limitations and future work for artificial piloerection.

II. Electrostatic piloerection

A. Physical principle

A charged electrode generates an electrostatic field that can exert forces over other charged objects. As the Coulomb's law expresses, $\mathbf{F} = \frac{q_1 q_2}{4\pi\varepsilon_0}\frac{\mathbf{r}_1-\mathbf{r}_2}{|\mathbf{r}_1-\mathbf{r}_2|^3}$ the force is attractive if the charges are of different polarity and repulsive if they are the same. Hairs below an electrode can get charged if the user is connected to ground or if the charge is induced in the hairs (Figure 2).

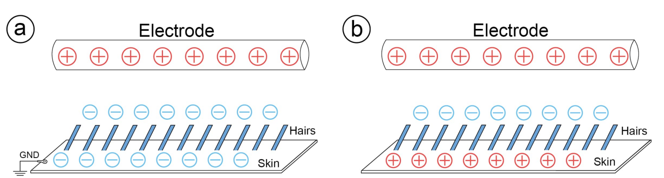

Fig. 2. Working principle of electrostatic piloerection. a) grounded user. b) ungrounded with induction.

B. Electrostatic generators

Modern high-voltage (HV) generators use flyback transformers [50] or Cockcroft-Walton multipliers [13]. These multipliers are composed of multiple stages of capacitors and diodes. Each stage doubles the input voltage and halves the current. These multipliers require an AC input and the output is DC.

In this paper, different high-voltage generators were created and compared with existing HV dc-dc converters. We created our own generators since the commercial ones do not reveal their full schematic, and some of them contain large capacitors that can store charge beyond safety levels. Also, we do not know the values of their limiting resistors. The generators that we built follow this design: a ZVS driver and a high-ratio transformer (both from the Walfront Boost Step-up), then a Cockcroft-Walton multiplier of different stages, a bleeder resistor between both sides of the multiplier ensures the discharge of the capacitors and the electrode, a limiting resistor controls the maximum current that can be delivered outside the circuit. The schematic can be seen in Figure 3. The whole high-voltage multiplier was encapsulated in transparent epoxy to avoid electric breakdowns and reduce leakage.

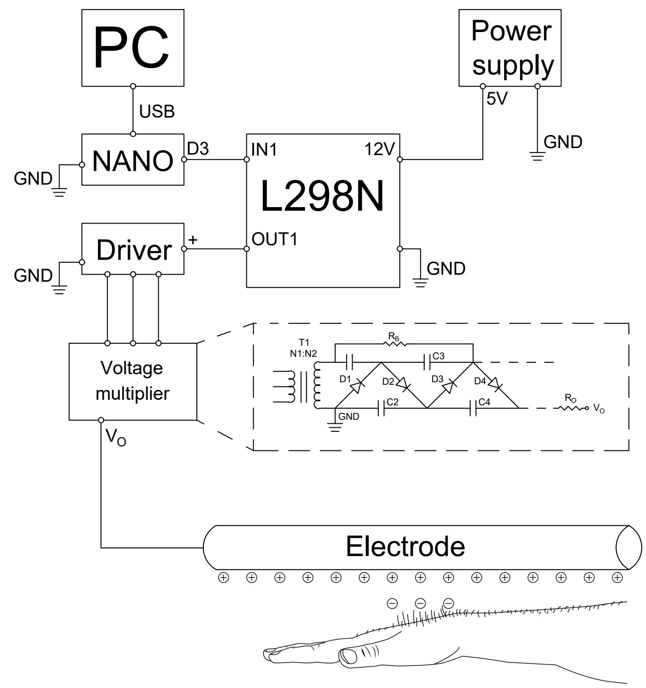

Fig. 3. Schematic of a system to deliver controlled electrostatic charge into an electrode, to attract the hairs below it. The PC is connected to an Arduino Nano for sending the desired intensity (from 0 to 255), the Arduino generates a PWM signal that is amplified by an L298N that powers the multiplier that outputs high voltage into the electrode. Inside the multiplier, there is a transformer (N1:N2 of 200) and multiple stages of a Cockcroft-Walton multiplier. R_b is the bleeder resistor and R_0 the limiting resistor.

Five generators were built:

- 6 and 1/2 stages: 6 capacitors (30KV, 0.1nF) on one side end 7 capacitors on the other side. It has 13 diodes (HV 20kV) placed to have a positive charge at the V out. It has 1 GOhm bleeder resistor and a 1 GOhm limiting resistor.
- 9 stages: 9 capacitors (20KV) at each side and 18 diodes. It has a 500 MOhm bleeder and a 500 MOhm limiting resistor.
- 6 stage: same as before.
- 5 stage: same as before but 30kV capacitors.
- 5 stage: same as before.

Commercially available generators were also tested:

- Cylindrical HV generator (advertised as 400 kV HC dcdc).
- FlyStick: toy Van der Graaft generator.
- High voltage generator (advertised at 5 kV).
- EMCO Cube F02 (rated at 4 kV for 12V input).

For the tests, the generators were powered with 3.3V and current limited at 2 A. We measured the charge on a cardboard electrode using a contactless NEWTRY electrostatic charge device (handheld 20kV). The generators can be seen in Figure 4 and their output charge on the electrode is shown in Figure 5. The charge can be controlled dynamically using different values for the duty cycle, the correspondence between the duty cycle and charge for the 9-stage generator can be seen in Figure 6. The 9-stage generator will be used for the rest of the paper, since it induces the largest charge in the electrode.

The selected generator (9-stage) has a bleeder resistor of 500 MOhm to remove any charge remaining in the capacitors when disconnected. Also, a limiting resistor of 500 MOhm limits the output to 0.4 mA even when operated at 200 kV, which is below the 2 mA recommended for high-voltage in the NIS guidelines [23]. Finally, the transformer and multiplier were potted in epoxy to avoid direct touch of the circuit and reduce leakage. This device consumed 1.9 A at 5V.

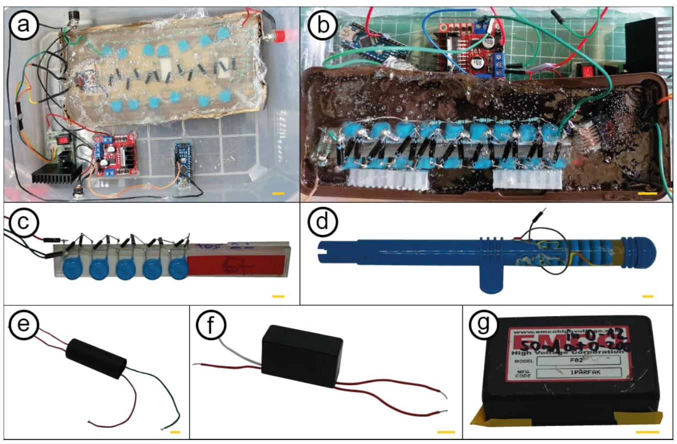

Fig. 4. Different generators tested. a) 6-stage potted and connected to the control circuit. b) 9-stages potted and with the control circuit. c) 5 stages. d) flystick. e) commercial HV generator, advertised as 400 kV and 5 kV (f). g) EMCO cube model F02. Scale bars are 1 cm.

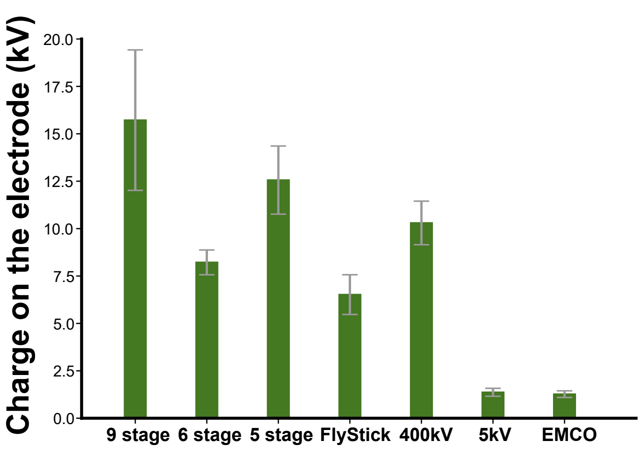

Fig. 5. Electrostatic charge generated on an 8 cm long 2 cm diameter, 1 mm thickness electrode made of cardboard. 5 measurements per device, error bars represent standard deviation.

1) Hairy skin replica: Fake hairy skin replicas were created to safely test the different HV generators and electrodes. The replicas were made of silicone polymer (PDMS) mixed with graphite to obtain similar conductivity to the human skin. Four different tests were made, mixing different quantities of

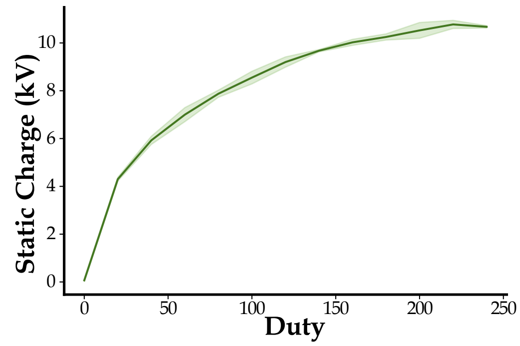

Fig. 6. Charge on the electrode as the duty cycle of the generator changed (from 0 to 255). 4 trials were conducted for values from 0 to 240, with steps of 20 on the duty cycle. The light-coloured area represents the standard deviation.

silicone and graphite. Two of the four samples were also mixed with isopropyl alcohol.

The skin contact resistance will usually be between 1kOhm and 100kOhms, depending on contact area, moisture, condition of the skin, and other factors [14]. The sample with the closest resistance to human skin had 2.25 vols of graphite per silicone and a resistance of 4 kOhms. Two hairy samples were made with these proportions. Hairs from a hair-dress practice mannequin were grafted before it dried, using a metallic grid to insert the hairs at an angle. After drying, the hairs were cut to the desired length. To determine if piloerection took part on the the fake hairy skin, a visual inspection for movement of the hairs was conducted, as can be seen in (Figure 7).

Fig. 7. Fake hairy skin made of silicone and graphite with fake hairs grafted, the cardboard electrode is above the hairs. Left) without electrostatic piloerection. Right) with electrostatic piloerection activated. Scale bar is 3 cm.

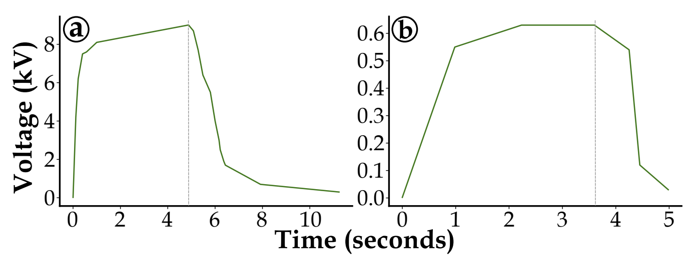

Fig. 8. Charge over time on the electrode (a) and on the skin (b). The generator was switched on at the beginning and switched off on the dashed vertical line.

C. Electrodes

We tested different shapes, sizes and materials for the electrode. We measured the charge on the electrode, on the fake skin and the residual charge in the skin after switching off the electrode. We also tested grounding the fake skin or leaving it ungrounded. The tested shapes were cylinders and flat electrodes. The materials: cardboard, plastic, cardboard with tinfoil inside, tinfoil and tinfoil with tape, and a coat of nail polish. The cylindrical tested electrodes can be seen in Figure 9. We decided to choose the longer cardboard cylinder because the charge on its surface was one of the highest, and also because the residual charge on the fake hairy skin was the lowest. The time it takes to charge and discharge the electrode as well as the charge measured on the skin over time can be seen in Figure 8. The charging takes less than 100 ms, and it reaches 9 kV in the electrode and 0.5 kV in the skin. Upon switching off, in 1 s the electrode discharges to 1 kV and the skin discharges completely. This electrode was the one inducing the largest hair movement and leaving the minimum residual charge. Flat electrodes with a conductive layer inside and a dielectric layer outside were used in exploratory research for electrostatic piloerection [16] but cylindrical electrodes made of cardboard provided better results for us, similar electrodes were used in the FlyWand toy stick (Figure 4.d). The cardboard electrode had a resistance larger than 5 GOhm (measured with a LEAGY VICTOR VC60B) and even on direct contact, no effect was perceived by the user.

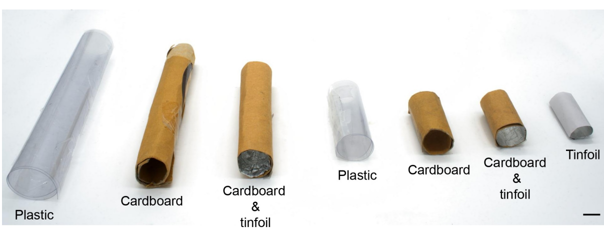

Fig. 9. Tested electrodes (left to right): plastic (20.3 cm long, 3.3 cm diameter), cardboard (17.7 cm long, 2.5 cm diameter), cardboard with tinfoil (13 cm long, 3 cm diameter), plastic (8 cm long, 3.1 cm diameter), cardboard (5.4 cm long, 2.5 cm diameter), cardboard with tinfoil (4.4 cm long, 2.5 cm diameter) and tinfoil (4.8 cm long, 2 cm diameter). Scale bar is 1 cm.

III. Psychophysical Studies

The objective of this user study is to determine the perception threshold for different body parts suitable for piloerection. In other words, what is the minimum intensity needed to make the stimuli perceptible by humans. Also, associated adjectives and emotions are listed by the participants when they received this stimulus.

A. Pre-selecting body parts

There are several body parts susceptible to piloerection: legs, pubis, arms, hands, nape, eyebrows or head. Piloerection is most often reported to be on the arms, nape, or legs [11]. We conducted a pilot study (N=6) to narrow down the number of suitable body parts. The legs and the pubis were discarded since people are not used to wearing devices on those areas; eyebrows, eyelashes or beards were discarded to avoid having electrodes in front of the face, yet they can be interesting areas for future studies. Therefore, we explored: the nape, upper forearm, lower forearm, wrist, back of the hand and fingers (Figure 10).

The stimulus was not perceived on the fingertips or palm. The fact that electrostatic piloerection was not perceived in glabrous skin suggests that the stimulus is perceived due to forces on the hairs or the follicles; thus, with our setup, the users were not perceiving ionic wind or other effects, they were perceiving piloerection (or another phenomenon that only happens on the hairy skin). A biological study of electrostatic piloerection is interesting but beyond the scope of the paper.

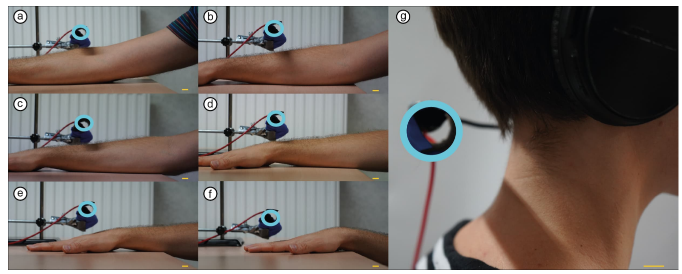

Fig. 10. Body parts on which piloerection was tested, the blue circle is the electrode. a) upper forearm, b) mid-forearm, c) low forearm, d) wrist, e) backhand, f) fingers, g) nape. The separation between the electrode and the skin was 3.5 cm. Scale bars are 1 cm.

Participants were sitting down wearing noise-canceling headphones and looking at a blank piece of board, the arm was resting on the table. The electrode was placed 3.5 cm above the target area, being held by a retort stand for the arm and with a flexible wire attached to the headphones for the nape. The different parts were excited at various electrostatic charges and the users were asked if they perceived the stimuli, a simple binary search was used to converge to a threshold in this pilot study.

The perception thresholds for the different body parts are shown in Figure 11. The wrist was more sensitive than the forearm. Also, the nape was found to be sensitive and has not been explored in the literature. The forearm is the traditional area, which has been most widely studied in the literature. Therefore, we selected: the wrist, nape and forearm for the full study. The wrist was sensitive and is usually more accessible than the forearm. The nape is an unexplored area that is not in the upper extremities, it is also accessible from head-mounted displays. The forearm is the most commonly explored area and is included as a point of comparison. We note that other parts can be interesting, but for a complete psychophysical study, we selected these three body parts.

B. Time Dynamics Pilot Study

Another pilot study was conducted to check the delays in the perception of this stimulus. We recorded over time: the activation of the electrostatic generator, the hairs' movement, and when the user reported feeling the stimulus. The data for four participants (2M, 2F) of varying hair on the forearm was captured with a camera (SVPRO 1080P 2.8-12mm) zoomed in on the area, two researchers inspected the footage to detect when the hairs started to move. People with more hair could feel the stimuli during the whole activation, whereas people

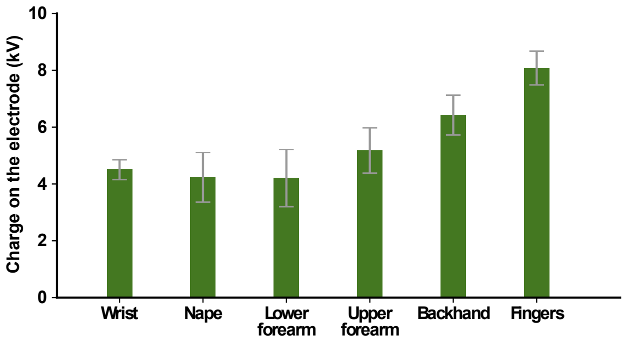

Fig. 11. Perception Threshold for different body parts from a pilot study. Error bars represent standard error from the 6 participants.

with less hair only felt the stimuli upon raising and falling of the hairs. All participants had a quick reaction time on the rising edge: (0.235s SD=0.189s) from activation to hairs raising, and (0.298s SD=0.196s) from activation to perception; on the falling edge there was some delay until the hairs fell (0.676s SD=1.405s), and (0.806s SD=1.376s) to perception.

In Figure 12 we show the aggregation of the participants for the time plots on device activation, hair movement and perceived stimulus. The short difference between perception and hair movement on the rising edge (63ms), may indicate that forces are applied on the hairs before observable movement happens, since typical reaction times are between (150ms and 300ms) [24]. On the falling edge, the difference was larger (130ms). Further investigation into this asymmetry could be interesting. This pilot study was conducted to have an approximated reaction time in order to inform the rest of the studies.

C. Perception Threshold Study

New participants (N=12; 7M, 5F) with average age (31.7 SD=9.74) were recruited for the study. The three selected body parts from the pilot study were the nape, forearm and wrist. They were counterbalanced in order. The users were sitting in front of the computer wearing noise-canceling headphones and reporting through a keyboard using the non-dominant hand, the dominant hand was the one stimulated. The experimental setup can be seen in Figure 13.

The perception threshold was estimated using a one-up/two-down adaptive staircase procedure with a two-alternative forced-choice paradigm. We followed the procedure described in [4] from an electrovibration study. Basically, two periods of time were indicated to the user and the stimulus was present only in one. As the user guessed correctly where the stimulus was, the intensity of the stimulus decreased, on failure there was a reversal and on two correct guesses, a positive reversal. We took the average of the last 3 reversals. The stimulus lasted 3 seconds and the up/down factors were (x1.26 for the coarse and x1.16 for the fine). An example of the measurements for a user can be seen in Figure 14.

The perception threshold staircase was performed for each of the body parts. Afterwards, the user filled in a questionnaire reporting free adjectives, similar experiences and differences between body parts. Also, they reported with a Likert scale (from 1 to 7) the level association for each body part of the stimulus with 6 emotions and 9 adjectives common from tactile stimulus. The answers for the free adjectives were filled in before showing the list of pre-selected adjectives. The whole procedure took an average of 35 minutes.

D. Results

1) Perception Threshold: The perception threshold averaged per user can be seen in Figure 15. The nape is still the most sensitive part but not significantly (ANOVA repeated measures: df=2, F=2.30, p=0.123) due to the large variance between users.

The hair amount was quantified by two evaluators from 1 (none) to 3 (abundant) for the nape, forearm and wrist from pictures of the different body parts, no disagreement was found. We found no correlation between the amount of hair and the sensitivity for nape (R=0.007, p=0.985), forearm (-0.498, p=0.119) or wrist (R=-0.442, p=0.174). These are not conclusive results but suggest that the amount of body hair does not affect the sensitivity to electrostatic piloerection, something that we have informally observed across all the studies; i.e., participants were able to feel piloerection despite their hairiness.

The correlations with age were (R=-0.103 p=0.749) for the nape, (R=0.496 p=0.10) for the wrist, and (R=0.368 p=0.239) for the forearm. Attending to sex, males were significantly hairier on the forearm (p=0.012) and wrist (p=0.017) than females. There was no difference in the sensitivity between genders (nape p=0.09, wrist p=0.75, forearm p=0.47). We note that our sample pool is not large enough, nor varied in age, to make these correlations generally applicable, but they highlight interesting trends for future research.

2) Free adjectives and descriptions: The free adjectives used to describe the sensation were: tingling (7 times), tickling 7, pleasant 5, cold 2, beating 2, electric 2, bubbling 2, soft 2, subtle 1, light, vibrating, relaxing, unpleasant, diffuse, focused, strong, amusing, pinching and friendly.

When the participants were asked about similar experiences they answered: having goosebumps 3, approaching a CRT 2, caresses 2, wind 2, touching another hand 1, insects, webs, phantom feeling of a phone notification, itchiness due to cold or heat, chill, awe from listening to music, wires that massage your head, electric shock and fear.

When asked about differences between body parts, some answers from the participants were: P1 *Nape feels more intimate and gradual, forearm more sudden, wrist more extended*, P2 *Forearm was harder to feel over a continuous stimulus, on the nape it was weaker, but I could feel it continuously.*, P3 *The nape was more on edge and delicate.*, P4 *Nape was more pleasant, almost erotic; wrist was neutral, the forearm was amusing and gratifying; perhaps it is something cultural.*, P5 *I have not felt anything in the wrist, in the nape I felt tickling, in the forearm pinching/shock.*, P6 *In the nape, I can feel my hair bristling, in the other areas I feel like cold air.*, P7 *Intensity was larger in the forearm x2.*, P8 *I can feel better the nape. As time passed I could perceive better the sensation.*, P9

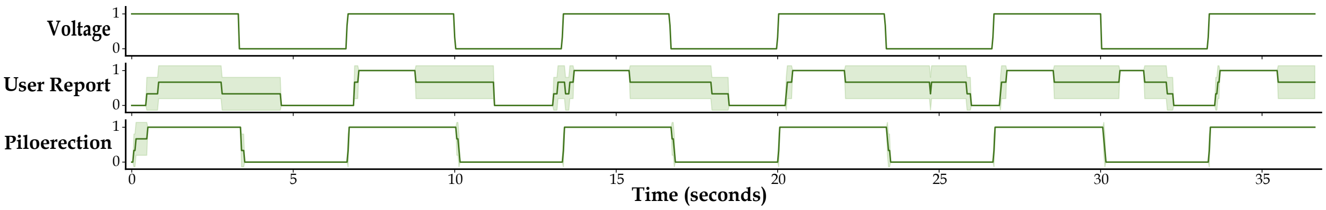

Fig. 12. Plots over time for the activation of the electrostatic field (Voltage), the perception of the user (User Report) and the rising of the hairs as captured by a camera (Pilorection). They are reported as 0 (off, no report, no movement; respectively) or 1 (on, user reporting, hairs moved).

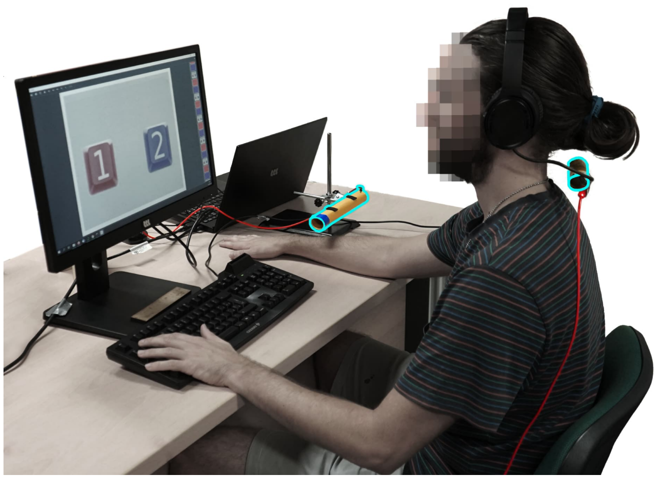

Fig. 13. Experimental setup for the user study of perception thresholds. There is an electrode above the forearm and above the nape (separation 3.5 cm). The user is in front of a computer to report the perception of the stimulus.

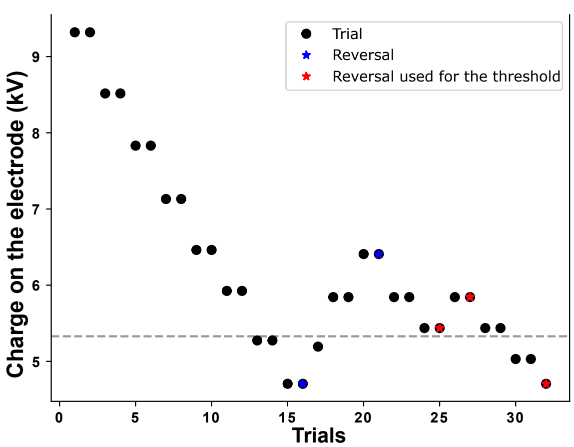

Fig. 14. Example of the staircase procedure from one of the participants to determine the perception threshold.

At high power I could feel at the sides, at low power I could feel at the center. In the nape, it felt like wind, at lower power felt like a swirl. In the forearm I felt my pulse, at lower power was like wind. In the wrist, the sensations extended into the hand and the forearm..

3) Emotions and adjectives: The Likert results for the association with emotions can be seen in Figure 16. The

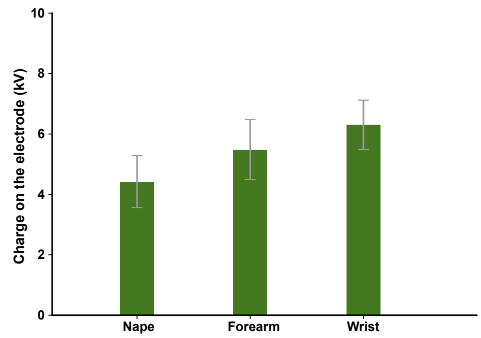

Fig. 15. Averaged perception thresholds (N=12 users) for different body parts. Scale bars represent standard error.

wrist has the weakest associations (almost none with fear and sadness), perhaps because we are more used to being touched in that area under common social interactions. The nape had the strongest emotional associations. The emotions associated with the stimulus were: surprise, excitement, happiness, fear, disgust and sadness; in order of popularity. In general, the nape had stronger or similar associations than the forearm, except for disgust. The general agreement that piloerection is associated with high arousal [3] (Surprise and Exciting) vs low arousal (Sadness) holds in these results. We note that this subjective self-reported feedback cannot be considered of significance, and it is presented more as an exploration.

The association with pre-selected adjectives commonly used in tactile studies can be seen in Figure 17. The most common adjectives were comfortable, pleasant and tingling. It is interesting to note that positive or neutral adjectives appear more than negative ones, at least in the absence of another stimulus apart from electrostatic piloerection.

IV. Pilot Experience Study

This pilot study tries to be a more organic experience in which piloerection augments an existing immersive experience. Our experiment is slightly inspired by the physiological theories that suggest that body responses are responsible for emotions, e.g., the James-Lange theory of emotion [21]. Although this theory and its variations are controversial, some modern interactive devices create artificial stimuli to try to elicit emotions; e.g., artificial tears for happiness or sadness [49].

We measure the physiological responses and self-reported subjective ratings of the users while they watched two im-

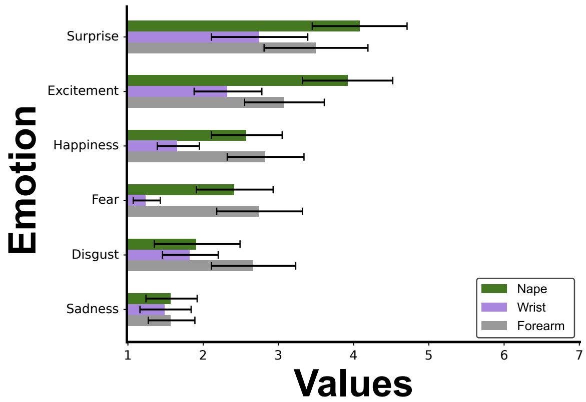

Fig. 16. Likert scale of the association with the stimulus and different emotions split by body parts. Being 1 no relation at all, and 7 totally related. Scale bars are standard error.

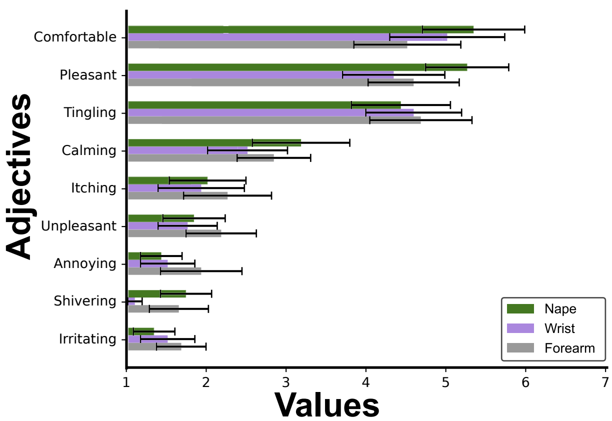

Fig. 17. Likert scale of the association with the stimulus and different adjectives split by body parts. Scale bars are standard error.

mersive videos related to fear, with and without piloerection applied on the nape. In the following subsections, we provide a rationale for selecting a body part, an emotion and a stimulus. We focused on one emotion, given that having multiple would require a between-subjects study to avoid cross-talk between the emotional states. Also, the lack of agreement on which emotions are connected to piloerection may indicate that a multi-emotion study is beyond the scope of a single paper based on the hardware and psychophysics.

A. Selecting a body part for piloerection

For the Pilot Experience, we selected the nape because it had the best sensitivity (Fig. 15). The nape also had stronger or the same emotional associations with the reported adjectives, except for disgust (Fig. 16). These differences were not significant and the main reason to pick the nape was that it is an unexplored area for piloerection and is easily accessible with an attachment on a head-mounted display that leaves the electrode suspended above the nape.

We refer as *PiloNape* to the application of contactless artificial electrostatic piloerection on the nape of the user.

B. Selecting an emotion

The set of emotions that generate piloerection remains unclear in the literature [33], but it is suggested that is an indication of peak moments (high arousal) [3], [12], [33]. Some studies point out that more chills and goosebumps occurred in response to negative valence [18].

We selected fear because it is high arousal and negative valence. Another interesting emotion would be anger since it also has high arousal and negative valence, yet this emotion does not appear connected to human piloerection in modern literature [33]. Surprise has high arousal and has been tested with piloerection [16] but the valence sign could be either positive or negative and no direct connection with surprise has been made in modern literature of emotional research [33].

C. Selecting the stimuli

Film clips are used in several studies to induce emotions [25], [29], [30], [40]. We tested the clips, and we were not fully convinced since they lacked context and building up, they did not provoke strong reactions in the researchers. Furthermore, we wanted to conduct a study in an immersive scenario, which also helps to avoid effects from the evaluation environment, virtual reality head-mounted displays are a good option for this.

We discarded VR video games since the ability of the participants with the controllers affects the results [37]; for example, somebody that has never played a horror game can get stuck and become frustrated instead of scared. We decided to use fear-related clips designed for VR environments. After watching a wide selection, we discarded clips that contain dolls or clowns, since pediophobia and coulrophobia are wide-extended and would bias the responses. Finally, we chose two similar clips to alternate them in the user study: 'Conjuring 2' [36] and 'Portal' [45]. Frames of the clips are shown in Figure 18.

Two researchers selected 3 moments of the clips to apply PiloNape. The stimuli were applied 1 second before the moment when tension was starting to build up, and remained activated for approximately 20 seconds. This is approximately the duration of the naturally occurring pilorection [5].

For the Conjuring clip, the timestamps are:

- 0:49 to 1:01: the man's spirit appears for the first time.
- 1:48 to 2:00: the nun's shadow appears, walks and goes out of the poster.
- 2:45 to 2:55: the last spirit appears.

For the Portal clip:

- 1:56 to 2:10: the cup starts moving and falls into the floor.
- 3:20 to 3:48: children scream and lights go on and off while the pythoness gets possessed.
- 4:23 to 4:41: the chair moves and the pythoness appears suddenly.

We searched for clips related to relaxation and pleasantness to play between the fear clips, so users could go back to a basal

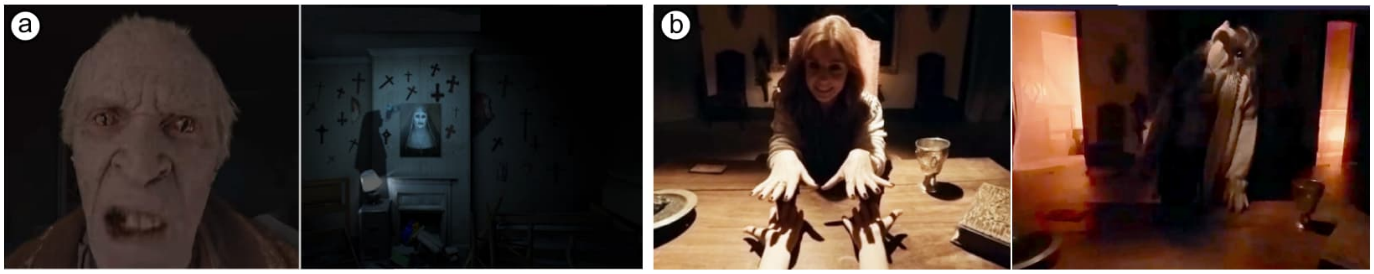

Fig. 18. Frames from the selected scary clips. a) Conjuring, b) Portal.

emotional state. We selected 'Aurora Borealis' [32] which had already been used by a previous research and combines relaxing visuals and music.

D. Measurements

We captured heart rate (HR) and galvanic skin response (GSR). Cardiovascular measures and skin conductance are indicators of physiological arousal and sympathetic activity (the higher the HR and GSR, the greater the anxiety) [22]. Biosignals were recorded using Neurobit Optima 4+ device [1], and heart rate with a finger pulsoximeter (Berry Electronics). The electrostatic piloerection did not affect the GSR and HR sensors, since no changes in the signals were detected upon activation and deactivation.

For the subjective measurements, we used the Self-Assessment Manikin (SAM) [8]. SAM is a non-verbal pictorial assessment technique that measures the valence, arousal, and dominance associated with a person's reaction to a stimulus. SAM is widely used in VR applications [26], [27], [39], [46], [48].

E. Procedure

Twelve new participants (7M, 5F; age=33.33 SD=13.9) took part in this pilot experience. The participant sat down in front of a table, wearing the HMD (Meta Quest 2), noise-canceling headphones with the audio from the video, as well as the GSR electrodes on the non-dominant hand fingers and the heart rate sensor in the index finger of the dominant hand. An attached camera captured the forearm of the non-dominant hand to check for piloerection. The setup can be seen in Figure 19.

The participant was informed about the experiment and signed the consent form. The sensors and the glasses were put on the user. Then, the user watched the first clip. After the first clip, they filled in a questionnaire. Afterwards, they watched a relaxing clip of the Aurora; then, the second scary clip. Finally, the last questionnaire was filled in. The procedure took an average of 35 minutes. The clips for fear were counterbalanced in order, and the application of PiloNape or not was also counterbalanced for each clip. This resulted in four groups: Cojuring NoPilo Portal Pilo, Cojuring Pilo Portal NoPilo, Portal Pilo Conjuring NoPilo, Portal NoPilo Cojuring Pilo. Repeating a clip for the same participant would have led to a very significant order effect, since we considered the clips one time experiences.

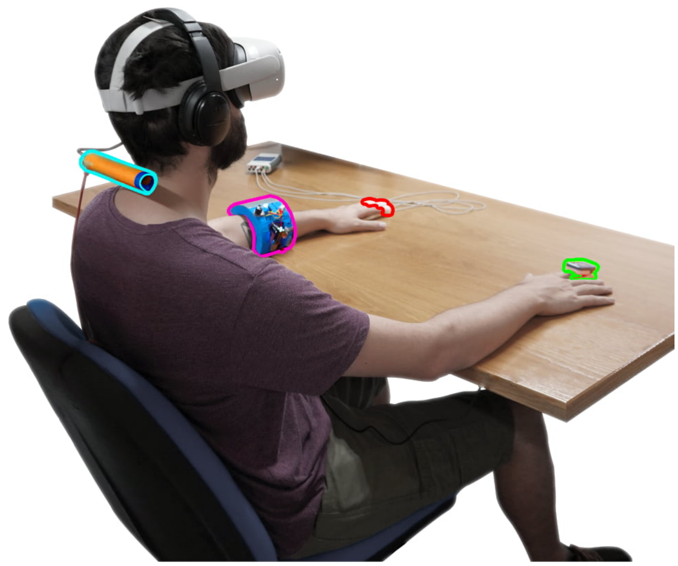

Fig. 19. A user conducting the pilot experience study. Wearing VR glasses (Quest 2) and noise-canceling headphones. The electrode (cyan) was above the nape at 3.5 cm. On the non-dominant hand, the galvanic skin response was measured with grounding on the ring and sensing on the index and heart fingers (red); a wearable close-zoom camera with illumination recorded the forearm, checking for piloerection (fuchsia). On the dominant hand, the heart-rate was measured with a pulsoximeter (green).

F. Results

G. Physiological

1) Heart-rate and galvanic skin response: In Figure 20 we show the aggregated data over time for users watching the two clips with PiloNape and no PiloNape. Looking closely in the HR and GSR, there are changes during the scary moments. We note that for both clips, scary moments 1 and 3 were sudden jump-scares, whereas moment 2 had more build-up. In the more abrupt scary moments (1 and 3), applying piloerection increased the sudden change of the heart-rate and GSR, whereas the effect of piloerection is less clear in the build-up moments (2).

Two plots for specific users (not aggregated) can be seen in Figure 21, in the first user (a sensitive one) the effect of piloerection can be clearly seen. The second user is less sensitive, yet when pilonape was applied, the heart rate had small.

The heart rate signals and galvanic skin response were preprocessed to extract features from the biosignals acquired pics/experience/Ag_HR_GSR_overtime_GreyLabesl_vertical.pdf

Fig. 20. Heart-rate (normalized) and Galvanic Skin response (Phasic) aggregated by users over time. The 3 scary moments are indicated between vertical dashed lines. The plot lines are the average and the coloured areas the standard deviation from the HR and GSR.

over time. The data were normalized to fit in the range [-1:1]. From the GSR signal, we extracted the tonic component, which describes slow changes (0- 0.16 Hz); and a faster-varying phasic component (0.16-2.1 Hz) [41]. Mean value and entropy were obtained for each measurement. The results are presented in Figure 22. The HR entropy, GSR entropy, GSR Tonic mean value, GSR Phasic mean and its entropy present higher data dispersion when applying PiloNape suggesting that participants experienced more varied physiological reactions throughout the experience. GSR entropy also shows higher values when PiloNape is applied. Differences between the conditions were found for GSR mean (p=0.003, Cohen's D = 0.18) and for GSR entropy (p=0.015, Cohen's D = 0.39), we note that even with Bonferroni corrections (p-value threshold adjusted from 0.05 to 0.006), GSR mean still presents significant differences.

2) Contagion Piloerection: Real piloerection happening on the arm of the users was captured with a camera mounted on the forearm (see Figure 23). Three researchers looked at the videos to detect if there was piloerection 10 seconds before or after the scary moments. Users reported the occurrence of piloerection correctly in 19 out of the 24 experiences, (χ^2=4.11 p=0.043); the guess of the user was considered correct if they reported piloerection during the experience and piloerection was observed by the researchers in any of the three scary moments (10 seconds before or after). We note that artificial piloerection was applied in the nape and that the piloerection on the forearm was a purely physiological reaction of the user. In the Portal clip, no piloerection happened without applying PiloNape, whereas all 6 people that were watching Portal with PiloNape got piloerection on the forearm. For the Conjuring clip, the effect was weaker (2 vs 3). The clip (Portal or Conjuring) may be having an effect as well as the application of piloerection, we do not consider 12 participants enough for mixed interaction effects. Consequently, we find these results interesting but not conclusive.

Fig. 21. Heart-rate over time for a sensitive user (a, b) and a non-sensitive user (c, d). (a) and (c) are for the clip Portal with no PiloNape, whereas (b) and (d) are for the clip Conjuring with PiloNape.

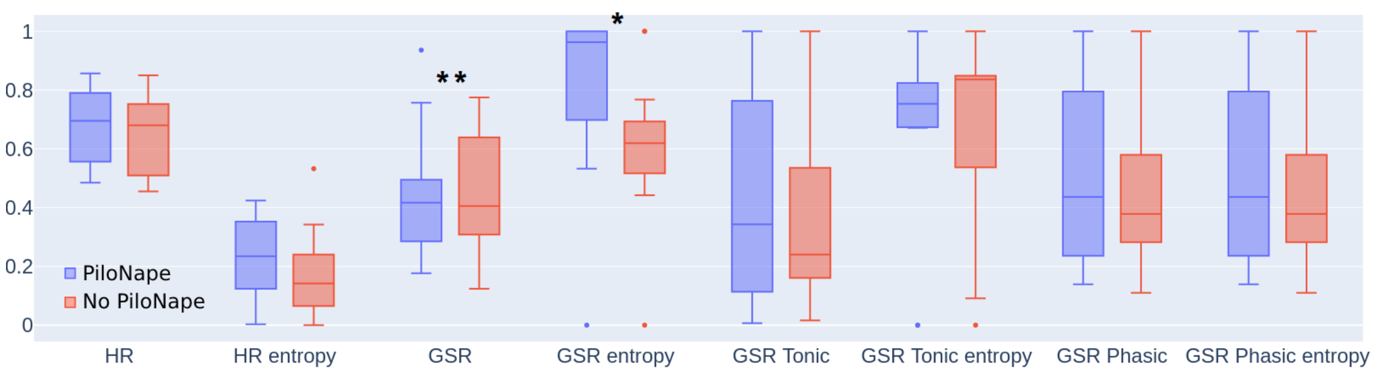

Fig. 22. Boxplot for the biosignals: heart-rate (HR), Galvanic Skin Response (GSR), GSR tonic component, GSR Phasic component. Calculated as mean and entropy for each condition.

H. Subjective

For the subjective measurements, we asked the users if they felt any of the following body sensations: shivers, goosebumps or nothing. The other question asked if the users felt as one of the following 8 adjectives: alarmed, tense, angry, scared, annoyed, distressed, frustrated or bored. More users reported shivers (5 vs 3) and goosebumps (6 vs 4) when PiloNape was applied but not significantly.

The results of subjective SAM questionnaires (valence, arousal and dominance) were not meaningful since participants had problems understanding valence, they thought the more scary the experience was, the better. Most users reported that they did not understand Dominance, even after explanations from the examiners. In any case, the differences were not significant. The rating of fear was slightly larger for the condition of PiloNape, but again, not significantly.

The adjectives selected for describing the experiences from a list of 6 were: Tense (6 times with PiloNape - 5 with no PiloNape), Alarmed (3-3), Fearful (2 - 1), Bored (0 - 2), Upset (0 - 1) and Frustrated (1 - 0).

V. Discussion

Apart from physiological and self-reported data, it could be interesting to capture behavioural information. More interactive experiences should be presented to the user, making the evaluations less replicable and structured but more realistic. For example, the user can play a horror game with zombies, a behavioural measurement would be the number of shots employed beyond what it is strictly necessary, since shooting more would imply a higher level of arousal.

We only explored fear. We planned to test sadness and awe, but on preliminary tests, we noticed that the clips, songs, or apps tested for awe were not eliciting those sensations on the researchers. We found a strong clip for sadness (Up from Pixar) that left various researchers emotionally affected for hours. Therefore, a larger user study with between-subjects (separated by emotion) or across different weeks is needed for multi-emotional testing.

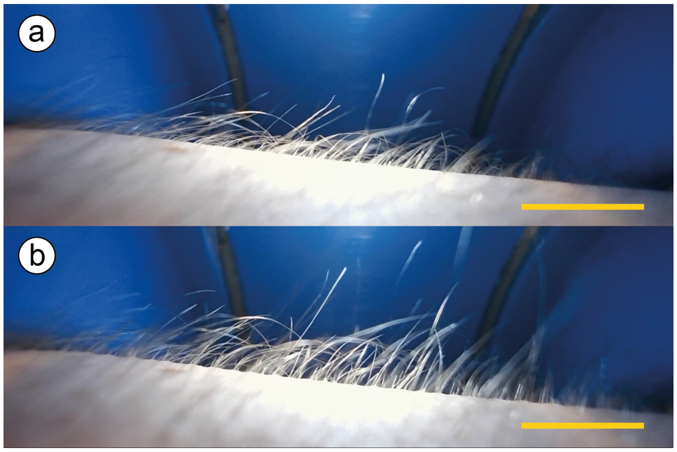

Fig. 23. Natural piloerection happening in the forearm. a) before piloerection. b) during piloerection. Scale bars are 1 cm.

The creation of spatially or intensity-varying patterns would provide richer stimuli. The spatially varying patterns can be done using various sequentially placed electrodes to simulate, for example, a caress on the forearm. The idea of using intensity varying patterns appeared when we were creating the timestamps for applying piloerection in the 2 clips, we wanted to make the intensity follow the music or have a blinking stimulus raising in frequency to build up tension. Naturally occurring piloerection does not have those dynamic patterns, but in future work, we would like to create complex piloerection patterns and check if they elicit different sensations in the users.

The distance from the electrode to the skin was set to 3.5 cm because it seemed a reasonable contactless distance to target the area without cross-talking to other areas. Yet, we experience the feeling of piloerection even when the electrode was 10 cm away, depending on the charge and size of the electrode. This can be interesting for desktop scenarios or public exhibitions, with a large electrode on top of a box that creates sensations when the hand (and wrist) is inside the box.

In PiloNape, we used an electrode above different body parts, but the whole user could be charged, making their hair and clothes to press or rub on the skin. This would be an alternative that does not require electrodes, the user would just stand on a platform to get charged, but should be accompanied by a close-loop system that removes the charge from the body to avoid unpleasant shocks when touching real-world objects afterwards. In PiloNape, the hairs get charged and attracted towards the electrode providing a localized sensation. Differently, when charging the whole body without an electrode, the sensation was more like subtle contact on the forearms, lower legs or head.

Reduced sensitivity with age has been reported with focused ultrasound [42]. In our study, we did not specifically target a wide range of age groups, yet we saw a negative correlation between age and sensitivity on the wrist as well as the forearm. Interestingly, the nape sensitivity was not correlated with age. A targeted study on the sensitivity of the nape at different ages may report that the area remains more sensitive than other areas to tactile stimuli despite ageing. This is important since the sensitivity to tactile stimuli from most haptic technologies decreases with age; the elder population may benefit tremendously from more affective virtual and remote experiences, including touch.

Electrostatic piloerection may seem niche or too exotic, and although the system can be integrated with head-mounted displays, it is hard to imagine VR systems shipped with it. Yet, it could be a compelling addition for more controlled environments that want to deliver an immersive or special experience like 4D cinemas, dining experiences, or museums.

VI. Conclusion

We have designed a device capable of generating an electrostatic field that causes artificial piloerection. The most appropriate generators and electrodes were tested on artificial hairy skin. Different parts of the body were tested in terms of their sensitivity to piloerection, a more detailed psychophysical study with perception thresholds and associated adjectives was performed in 3 areas: nape, wrist, and forearm. The changes that artificial piloerection has on the physiological reactions of the user was tested while visualizing two immersive videos related to fear; artificial piloerection on the nape to augment the immersive experience. Piloerection is a contactless approach to haptics that could be used by designers to enhance movies, video games, or museum experiences.

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References

[1] Neurobit. http://www.neurobit.com.pl/, 2022.

[2] Imtiaj Ahmed, Ville Harjunen, Giulio Jacucci, Eve Hoggan, Niklas Ravaja, and Michiel M Spapé. Reach out and touch me: Effects of four distinct haptic technologies on affective touch in virtual reality. In *Proceedings of the 18th ACM International Conference on Multimodal Interaction*, pages 341–348, 2016.

[3] Scott Bannister and Tuomas Eerola. Suppressing the chills: Effects of musical manipulation on the chills response. *Frontiers in Psychology*, 9:2046, 2018.

[4] Olivier Bau, Ivan Poupyrev, Ali Israr, and Chris Harrison. Teslatouch: electrovibration for touch surfaces. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, pages 283–292, 2010.

[5] Mathias Benedek and Christian Kaernbach. Physiological correlates and emotional specificity of human piloerection. *Biological psychology*, 86(3):320–329, 2011.

[6] Roger Boldu, Sambhav Jain, Juan Pablo Forero Cortes, Haimo Zhang, and Suranga Nanayakkara. M-hair: Creating novel tactile feedback by augmenting the body hair to respond to magnetic field. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pages 323–328, 2019.

[7] Roger Boldu, Mevan Wijewardena, Haimo Zhang, and Suranga Nanayakkara. Maghair: A wearable system to create unique tactile feedback by stimulating only the body hair. In *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services*, pages 1–10, 2020.

[8] Lang PJ. Bradley MM. Measuring emotion: the self-assessment manikin and the semantic differential. *J Behav Ther Exp Psychiatry*, 25(1)::49–5, 1994.

[9] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. Ultrahaptics: multi-point mid-air haptic feedback for touch surfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*, pages 505–514, 2013.

[10] Polona Caserman, Clemens Krug, and Stefan Göbel. Recognizing full-body exercise execution errors using the teslasuit. *Sensors*, 21(24):8389, 2021.

[11] Daniel G Craig. An exploratory study of physiological changes during "chills" induced by music. *Musicae scientiae*, 9(2):273–287, 2005.

[12] Charles Darwin and Phillip Prodger. *The expression of the emotions in man and animals*. Oxford University Press, USA, 1998.

[13] Edgar Everhart and Paul Lorrain. The cockcroft-walton voltage multiplying circuit. *Review of Scientific Instruments*, 24(3):221–226, 1953.

[14] Raymond M Fish and Leslie A Geddes. Conduction of electrical current to and through the human body: a review. *Eplasty*, 9, 2009.

[15] Shogo Fukushima and Hiroyuki Kajimoto. Chilly chair: facilitating an emotional feeling with artificial piloerection. In *ACM SIGGRAPH 2012 Emerging Technologies*, pages 1–1. 2012.

[16] Shogo Fukushima and Hiroyuki Kajimoto. Facilitating a surprised feeling by artificial control of piloerection on the forearm. In *Proceedings of the 3rd Augmented Human International Conference*, pages 1–4, 2012.

[17] LR Gavrilov, EM Tsirulnikov, and I ab I Davies. Application of focused ultrasound for the stimulation of neural structures. *Ultrasound in medicine & biology*, 22(2):179–192, 1996.

[18] Oliver Grewe, Björn Katzur, Reinhard Kopiez, and Eckart Altenmüller. Chills in different sensory domains: Frisson elicited by acoustical, visual, tactile and gustatory stimuli. *Psychology of Music*, 39(2):220–239, 2011.

[19] Sidhant Gupta, Dan Morris, Shwetak N Patel, and Desney Tan. Airwave: Non-contact haptic feedback using air vortex rings. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing*, pages 419–428, 2013.

[20] Seki Inoue, Yasutoshi Makino, and Hiroyuki Shinoda. Active touch perception produced by airborne ultrasonic haptic hologram. In *2015 IEEE World Haptics Conference (WHC)*, pages 362–367. IEEE, 2015.

[21] William James. What is an emotion? *Mind*, os-IX(34):188–205, 04 1884.

[22] Elina E Ketonen, Visajaani Salonen, Kirsti Lonka, and Katariina Salmela-Aro. Can you feel the excitement? physiological correlates of students' self-reported emotions. *British Journal of Educational Psychology*, page e12534, 2022.

[23] Michinari Kono, Takumi Takahashi, Hiromi Nakamura, Takashi Miyaki, and Jun Rekimoto. Design guideline for developing safe systems that apply electricity to the human body. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 25(3):1–36, 2018.

[24] Robert J Kosinski. A literature review on reaction time. *Clemson University*, 10(1):337–344, 2008.

[25] Paul Lemmens, Floris Crompvoets, Dirk Brokken, Jack Van Den Eerenbeemd, and Gert-Jan de Vries. A body-conforming tactile jacket to enrich movie viewing. In *World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 7–12. IEEE, 2009.

[26] Benjamin Li, Jeremy Bailenson, Adam Pines, Walter Greenleaf, and Leanne Williams. A public database of immersive vr videos with corresponding ratings of arousal, valence, and correlations between head movements and self report measures. *Frontiers in Psychology*, 8, 12 2017.

[27] Dan Liao, Lin Shu, Guodong Liang, Yingxuan Li, Yue Zhang, Wenzhuo Zhang, and Xiangming Xu. Design and evaluation of affective virtual reality system based on multimodal physiological signals and self-assessment manikin. *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, 4(3):216–224, 2020.

[28] Benjamin Long, Sue Ann Seah, Tom Carter, and Sriram Subramanian. Rendering volumetric haptic shapes in mid-air using ultrasound. *ACM Transactions on Graphics (TOG)*, 33(6):1–10, 2014.

[29] Antonio Maffei and Alessandro Angrilli. E-movie-experimental movies for induction of emotions in neuroscience: An innovative film database with normative data and sex differences. *Plos one*, 14(10):e0223124, 2019.

[30] Naveen Masood and Humera Farooq. Investigating eeg patterns for dual-stimuli induced human fear emotional state. *Sensors*, 19(3):522, 2019.

[31] Francis McGlone, Ake B Vallbo, Hakan Olausson, Line Loken, and Johan Wessberg. Discriminative touch and emotional touch. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, 61(3):173, 2007.

[32] Jonathon McPhetres. Oh, the things you don't know: awe promotes awareness of knowledge gaps and science interest. *Cognition and Emotion*, 33(8):1599–1615, 2019.

[33] Jonathon McPhetres and Janis H Zickfeld. The physiological study of emotional piloerection: A systematic review and guide for future research. *International Journal of Psychophysiology*, 179:6–20, 2022.

[34] Håkan Olausson, Y Lamarre, H Backlund, C Morin, BG Wallin, G Starck, S Ekholm, I Strigo, K Worsley, ÅB Vallbo, et al. Unmyelinated tactile afferents signal touch and project to insular cortex. *Nature neuroscience*, 5(9):900–904, 2002.

[35] Jerome Perret and Emmanuel Vander Poorten. Touching virtual reality: a review of haptic gloves. In *ACTUATOR 2018; 16th International Conference on New Actuators*, pages 1–5. VDE, 2018.

[36] Warnet Bros. Pictures. The conjuring 2 - experience enfield vr 360 [hd], 2016.

[37] Denise T. Quesnel and Bernhard E. Riecke. Are you awed yet? how virtual reality gives us awe and goose bumps. *Frontiers in Psychology*, 9, 2018.

[38] Priscilla Ramsamy, Adrian Haffegee, Ronan Jamieson, and Vassil Alexandrov. Using haptics to improve immersion in virtual environments. In *Computational Science–ICCS 2006: 6th International Conference, Reading, UK, May 28-31, 2006. Proceedings, Part II 6*, pages 603–609. Springer, 2006.

[39] Radiah Rivu, Ruoyu Jiang, Ville Mäkelä, Mariam Hassib, and Florian Alt. Emotion elicitation techniques in virtual reality. In *Human-Computer Interaction – INTERACT 2021: 18th IFIP TC 13 International Conference, Bari, Italy, August 30 – September 3, 2021, Proceedings, Part I*, page 93–114, Berlin, Heidelberg, 2021. Springer-Verlag.

[40] Ewa Siedlecka and Thomas F Denson. Experimental methods for inducing basic emotions: A qualitative review. *Emotion Review*, 11(1):87–97, 2019.

[41] Rajiv Ranjan Singh, Sailesh Conjeti, and Rahul Banerjee. A comparative evaluation of neural network classifiers for stress level analysis of automotive drivers using physiological signals. *Biomedical Signal Processing and Control*, 8(6):740–754, 2013.

[42] Yatharth Singhal, Haokun Wang, Hyunjae Gil, and Jin Ryong Kim. Mid-air thermo-tactile feedback using ultrasound haptic display. In *Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology*, pages 1–11, 2021.

[43] Rajinder Sodhi, Ivan Poupyrev, Matthew Glisson, and Ali Israr. Aireal: interactive tactile experiences in free air. *ACM Transactions on Graphics (TOG)*, 32(4):1–10, 2013.

[44] Daniel Spelmezan, Deepak Ranjan Sahoo, and Sriram Subramanian. Sparkle: Hover feedback with touchable electric arcs. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 3705–3717, 2017.

[45] Futura VR Studio and The Dream VR. Portal, 2018.

[46] Feng Tian, Xiaofei Hou, and Minlei Hua. Emotional response increments induced by equivalent enhancement of different valence films. pages 213–218, 05 2020.

[47] Olivier AJ Van der Meijden and Marlies P Schijven. The value of haptic feedback in conventional and robot-assisted minimal invasive surgery and virtual reality training: a current review. *Surgical endoscopy*, 23:1180–1190, 2009.

[48] Tianhua Xie, Mingliang Cao, and Zhigeng Pan. Applying self-assessment manikin (sam) to evaluate the affective arousal effects of vr games. In *Proceedings of the 2020 3rd International Conference on Image and Graphics Processing*, ICIGP 2020, page 134–138, New York, NY, USA, 2020. Association for Computing Machinery.

[49] Shigeo Yoshida, Takuji Narumi, Tomohiro Tanikawa, Hideaki Kuzuoka, and Michitaka Hirose. Teardrop glasses: Pseudo tears induce sadness in you and those around you. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–12, 2021.

[50] Xiangjun Zhang, Hankui Liu, and Dianguo Xu. Analysis and design of the flyback transformer. In *IECON'03. 29th Annual Conference of the IEEE Industrial Electronics Society (IEEE Cat. No. 03CH37468)*, volume 1, pages 715–719. IEEE, 2003.