M-Hair: Creating Novel Tactile Feedback by Augmenting the Body Hair to Respond to Magnetic Field

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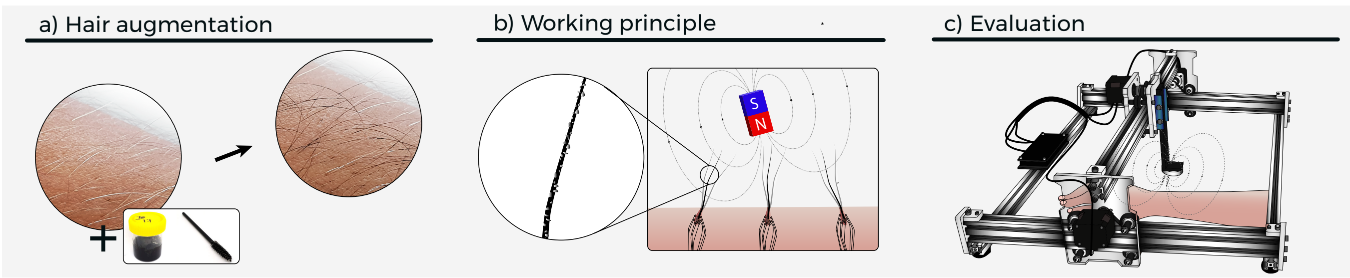

Figure 1. a) Forearm Hair of participant after applying passive magnetic cosmetics. b) The hairs are attracted by the magnetic fields providing tactile feedback. c) Setup of the evaluation with a CNC engraver (wooden enclosure not shown)

ABSTRACT
In this paper, we present M-Hair, a novel method for providing tactile feedback by stimulating only the body hair without touching the skin. It works by applying passive magnetic materials to the body hair, which is actuated by external magnetic fields. Our user study suggested that the value of the M-hair mechanism is in inducing affective sensations such as pleasantness, rather than effectively discriminating features such as shape, size, and direction. This work invites future research to use this method in applications that induce emotional responses or affective states, and as a research tool for investigations of this novel sensation.

CCS Concepts
•**Human-centered computing** → **Haptic devices;**

Author Keywords
Hair; Hair interfaces; Non-contact Tactile Stimulation; Magnetic Actuation.

INTRODUCTION
Human body hair extends the sense of touch beyond the skin surface. It detects minute contacts caused by e.g., air flow or insects, providing uniquely subtle sensations. In fact, rich in C tactile (CT) neurons, a highly sensitive type of mechanoreceptor, the human hairy skin has been linked to emotional touch (pleasantness, comfort, etc.), while glabrous skin (hairless skin) has been more related to discriminative touch (pressure, vibration, slip, and texture) [2, 21, 23].

While most existing work on haptics address skin and hair without distinction [5], selectively addressing the hair alone might enable more targeted haptic display and enhance the sense of touch [27] in applications such as reducing pain [9, 19, 24] or inducing pleasantness [1, 7, 20, 24].

M-Hair (Magnetic Hair) is a novel technique for creating tactile feedback by only stimulating the body hair. After mixing with hair products (e.g., gel or wax), magnetically responsive materials (e.g., iron powders) can be easily applied to the hair. Then, the augmented hair can be stimulated by an external magnetic field (e.g., through electromagnets or permanent magnets). The movement or change of the magnetic field strength induces varying sensations. This way, M-Hair generates a subtle tactile sensation without physical contact, and reduces the challenge of precise mechanical hair stimulation to the generation and control of a magnetic field.

In this work, we developed a proof-of-concept system to investigate the feasibility of M-Hair. A user study was then performed to understand the perceptual characteristics and limitations of dynamic stroke presented by M-Hair, including discrimination of shape, size, direction, and location. Users described the unique sensation M-Hair generated as pleasant and windy.

With M-Hair, we further envisage the magnetic augmentation of the human body to become a safe, socially compliant, and practical approach for interacting on and with the human body.

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RELATED WORK

Non-Contact Haptics

Despite large volumes of previous research, most techniques presenting haptic stimuli rely on physical contact between the actuator and the skin and are often intrusive with the need to attach electronics on the human body [5]. There is limited research addressing the intrusiveness of haptic displays with non-contact stimulation [31]. Besides removing the need for placing electronics on the body, with non-contact techniques, the physical form of the device does not restrict the area of actuation. Two of the most developed and explored techniques to apply non-contact haptic stimulation are air and acoustic.

Air Based: AIREAL [28] enables users to feel 3D objects and textures in the free air, by projecting air vortices to the users' skin. HAIR [30] is a haptic device that provides a surface tactile stimulation by using an air jet and a robotic structure.

Acoustic based: UltraHaptics [3] enables multi-point haptic feedback by creating focused ultrasounds through an array of ultrasonic speakers. A study has also investigated the resolution of a similar system [11].

Compared to these existing non-contact haptic technologies, M-Hair differs in that it targets the hair and not the skin, which generates a unique, subtle, and soft sensation.

Hair Augmentation

Previous research on augmenting hair focused on exploring the usage of human head hair as an input/output interface. As an example, the HäirIÖ project [6] explored the usage of the hair as a touch input and visual and haptic output. It augmented the hair with thermochromic pigments and shape memory alloy to change its color and shape. It targeted applications in style change, social engagement, public display, and haptic notifications. Also, Hairware [32] allowed touch input on the hair by embedding conductive strands. Finally, other work, such as SmartWig [29] explored the potential of creating artificial hair with embedded electronics.

These previous approaches placed electronics near or in the hair, limiting the form factor and the type of hair that can be stimulated. The working mechanism of M-Hair does not require electronics to be in direct contact with or tethered to the human body.

Skin Augmentation

With the miniaturization of electronics and the availability of soft electronics, a growing number of research focused on on-body devices and skin interfaces. They transformed the human skin as a venue for input and output. Research such as DuoSkin [15], multi-touch skin [22], iSkin [34] and Skinmarks [35] used the human skin as a venue for touch input. Other research have focused on the use of skin as a venue for output. The Tacttoo [36] project introduced an electro-tactile interface in the form of a temporary tattoo/second skin. SkinMorph [14] created skin interfaces with a programmable texture, whose rigidity changes in response to temperature. Earthtones [13] explored the use of chemicals on the skin, which changes color as a visualization of environmental factors. Regardless of input or output, existing skin interfaces rely on placing electronics in direct contact with the skin, thus creating limitations in scalability, flexibility, and the intrusiveness of the electronics. M-Hair, on the other hand, augments the hair with passive materials similar to everyday skin products, such as cosmetics, lotions and gels. In this way, it supports interaction through ambient and familiar skin and hair add-ons without creating feelings of intrusion among users, as evidenced by our user studies.

M-HAIR WORKING PRINCIPLE

The human hair consists of protein filaments that grow from hair follicles inside the skin [25]. Apart from warmth and protection, human hair also has a significant role as a sensory organ. Different from human glabrous skin (hairless skin), which is innervated by mechanoreceptors sensitive to deformation, vibration, and slippage, human hairy skin is richly innervated with C tactile afferents, which is a highly sensitive type of neuron [18]. The C tactile afferents are found to be related to pleasant touch [10, 17], and to mediate pain [19]. The working principle of M-Hair is to coat human hair with magnetically responsive materials, so that an external magnetic field can activate the hair without physical contact or directly stimulating the skin (Figure 1b). We hypothesize that actuating the hair alone creates a unique subtle tactile sensation that would otherwise be masked by stronger sensations when directly actuating the skin.

FORMATIVE USER STUDY

We conducted a formative user study to: 1) understand the perceptual characteristics, limitations and potential resolution of the M-Hair sensation; and 2) assess user comfort and acceptance of the physical augmentation of the hair.

Apparatus: To conduct the user study, we modified a 2D laser engraver[1], by replacing the header of the engraver with a rare-earth Neodymium permanent magnet (N45) with a pull force of 33.62kg. The engraver software[2] was used to present 2D strokes in a large area (50cm $\times$ 50cm). The entire system was covered with a wood enclosure to reduce the sound of the engraver, as well as to block the users' view to prevent potential confusion from seeing the operation of the system. The participants were asked to place their left arm under the laser engraver (Figure 1c). A wooden platform was used to align the top of the forearm to the working plane of the engraver, to ensure uniform magnetic field strength at different locations on the arm. The height of the header was adjusted so that the magnet is 25mm above the forearm.

Magnetic Material Recipe: To augment the body hair with magnetic properties, we mixed magnetic particles and a carrier that affixes the particles to the hair. To be safety-compliant, we used commercially available cosmetic products. For the magnetic particles, we chose a face mask[3] that contains a high concentration of iron particles. For the carrier, we used a hair

[1] http://wiki.eleksmaker.com/doku.php?id=elekslaser_a3_pro
[2] http://lasergrbl.com/
[3] https://www.drbrandtskincare.com/products/magnetight

wax[4]. The ingredients were mixed in a centrifugal mixer[5] for 3 minutes at 2500rpm.

Participants: We invited 6 participants aged between 25 and 29 (*M*=26, *SD*=2.95); 1 female and 5 males. On average, the participants had about 10 (*SD*=0.5) hairs per cm^2 with an average length of 20.5mm (*SD*=6.6mm). The experiment lasted for 40-60 minutes. The participants did not receive any remuneration.

Procedure: First, the magnetic material was applied on the left posterior forearm of the participants (Figure 1a). Then, the participants placed the forearm under the apparatus (Figure 1c) in the wooden enclosure. The platform was then adjusted to align the top of the forearm with the working plane of the engraver. The distance between the magnet and the forearm was calibrated at a fixed distance of 25mm, equivalent to a magnetic field of about 650 Gauss. The speed was decided to be 3cm/s, as suggested in previous research on affective touch [20]. The choice of forearm as the feedback area is based on the availability of body hair, as well as recommendations in previous research [21],

The structure of the experiment is as follows: 1) The participants were exposed to a 1-minute haptic stimulation and were asked to describe the sensation they perceived with several phrases or sentences, as well as to rate how relevant the description was to the sensation. 2) A set of patterns were presented in a random order (Figure 2c) on the forearm, and the participants were asked to draw them. The participants were not instructed as to what specific aspect of the stimuli they should focus on (e.g., shape, size, direction, or position). This was intentionally designed to be ambiguous and to test whether certain aspects are naturally noticeable by the participants. 3) The participants were asked to tell the direction of 6 circles (r=2cm), 3 clockwise and 3 anti-clockwise, presented in a random order. 4) The participants were asked to rank by size a set of 3 circles ($r \in \{1\text{cm}, 2\text{cm}, 3\text{cm}\}$) and a set of 3 lines (4cm, 6cm, 10cm). 5) 6 horizontal lines with 2cm spacing were presented in a random order on the forearm. Participants were asked to draw the perceived location for each image on the forearm. 6) Finally, participants completed a questionnaire regarding comfort, intrusiveness, and the noticeability of the hair augmentation.

Results

Subjective Descriptions: From the 6 participants, we collected a total of 25 descriptions of the tactile sensation, and the relevance for each. The 3 most mentioned descriptions from all participants were: *windy* (number of mentioned participants *P*=6, average relevance *R*=4), *pleasant* (*P*=4, *R*=4.3), and *touch* (*P*=3, *R*=4.3). Other relevant words the participants suggested include *unique*, *smooth*, *ticklish*, and *gentle*. According to the affective ratings of ~14k English words [33], all these descriptions are associated with positive valence (between 6 and 7.42) and slightly calm arousal states (2.76 to 4.9). Although affective states could be manipulated through various factors, using the hair stimulation alone might be able to consistently induce a calm and positive affective state.

(a) Location - Lines

	1	2	3	4	5	6
1	5	1	0	0	0	0
2	1	5	0	0	0	0
3	0	0	6	0	0	0
4	0	0	0	5	1	0
5	0	0	0	1	3	2
6	0	0	0	0	2	4

(b) Lines

	Small	Medium	Large
Small	6		
Medium		6	
Large			6

Circles

	Small	Medium	Large
Small	5	1	
Medium		4	2
Large	1	1	4

(c)

	○	□	△	‖	=	zigzag
Correct	2	0	0	3	2	3
Incorrect	4	6	6	3	4	3

Figure 2. Confusion matrices for a) position discrimination of line strokes, and b) direction discrimination. And c) patterns used for shape reproduction and their accuracies.

Perceptual Discrimination: Multiple discriminative features of the stroke stimuli, such as shape, size, direction, and location were evaluated. Participants performed poorly in shape recognition (Figure 2c), with the most accurately drawn shape being the vertical line, as well as zigzag, at a mere 50% accuracy. Comparatively, simple shapes, such as circles or lines were perceived more accurately compared to more detailed loops (squares and triangles). Interestingly, participants performed well when aware of the specific 2D feature (size or location) to discriminate. Figure 2a shows the confusion matrix for position discrimination of the lines, whose number indicates its relative location. Noticing that confusions only happen between adjacent lines which are 2cm apart, it can be postulated that users would be able to differentiate the relative position of strokes with a minimum resolution of 4cm. Further studies with a larger number of people are needed to measure the exact position differentiation resolution. For size discrimination (Figure 2b), participants perfectly discriminated between line sizes, but had some confusion between large and medium circles. For loop direction discrimination, there exist large individual differences, possibly related to the amount of hair. The two more hairy participants reported all 6 directions correctly, while the less hairy participants merely reported 1 correctly.

Comfort and intrusiveness: With a 5-point Likert scale (1 being *Strongly Disagree*, 5 being *Strongly Agree*, participants marked several statements regarding the overall comfort and intrusiveness of the hair (not the actuation apparatus). All the statements were crafted in a negative tone (e.g., "*The usage of this product creates physical discomfort.*"). The participants did not perceive strong physical discomfort (*M*=1.83, *SD*=0.75). They also reported that this augmentation did not restrict their arm movement (*M*=1.33, *SD*=0.51). Par-

[4]https://www.gatsbyglobal.com/en/product/moving-rubber/index.html#grunge-mat
[5]http://www.thinkymixer.net/products/item-all/ce-certified-model/are-250ce.html

ticipant 2 reported that *"even after some time, I almost forgot that I was wearing a product"*. Participants were generally neutral regarding intrusiveness of the augmentation (*M*=3, *SD*=0.63). The main concerns includes social acceptance, and some wished that the color of the magnetic material were the same as their hair.

Discussion

The results showed a low discriminative accuracy, particularly for shape recognition, while the users' sensations were generally associated with positive and calming emotions. This finding aligns with existing work highlighting the linkage between C tactile neurons and affective touch. Interestingly, users exhibited some level of discrimination with size, direction, and location of the stimuli, which could be the subject of investigations for upstream neuroscience research.

The resolution of our proof-of-concept haptic display device is dependent on several factors. First, the traversal speed of the laser engraver is limited, resulting in a longer display time for larger shapes. In our study, we set the speed at $3cm/s$ according to previous work on affective touch [20]. Further research is needed to better understand the effect of speed on user perception. Second, the size of the permanent magnet affects how much hair can be actuated simultaneously, thus affecting the spatial resolution. Third, apart from the strength of the magnetic field, the shape and distribution of the magnetic field on the hairy surface might affect the sensation and needs further investigation.

During the study, we observed substantial individual differences in the hair anatomy, such as length, shape, strength, and density. The specific influences of these factors on perception requires further study. As an example, the female participant had a hair length of 8mm, whereas some of the male participants had hair lengths up to 25mm. Future studies should account for or control such individual differences.

LIMITATIONS AND FUTURE WORK

Recipes and Safety: The most important concern of hair and skin augmentation is the safety. It is also one of the most important limiting factors in recipe development. In our user studies, we ensured safety compliance by using commercially available products. We have started investigating several recipes with varying ingredients and concentrations, focusing on how these recipes affect the magnetic properties of the augmented hair.

Magnetic Field Safety: The human body is generally safe with magnetic fields. However, caution is needed when dealing with large and rapidly-changing magnetic fields near the human body [8, 26]. In our studies, we mainly used "small", 650 Gauss, constant magnetic fields drawn at a slow speed by the laser engraver, which is safe for the human body. Future work should take extreme care to ensure a safe operating magnetic environment when exploring the frequency response of the magnetically augmented hair. Also, it is extremely dangerous and thus should be forbidden for people with implants, such as a heart pacemaker.

Individual Differences: Large differences exist in hair properties, due to various factors, such as race and gender. Our study has exposed such differences in the length, stiffness, and density of hair on the forearm, which are main factors influencing the user experience. Future studies can aim to develop further understandings of the impact of such factors on the user experience.

Apparatus: Our study apparatus was designed to reliably present the stimuli and facilitate the user studies. The combination of rare-earth permanent magnets and a repurposed laser engraver provides a safe and simple way to control a strong magnetic field. There are other methodologies of generating and controlling a magnetic field. For example, with electromagnets, we could control the frequency and strength of the magnetic field, to generate more detailed effects, such as constant wind. Also, sequentially activating multiple electromagnets to move the magnetic field in certain directions, creates moving sensations without mechanical movement. Finally, the usage of superconductors could produce large magnetic fields, and potentially actuate the hair from a further distance, creating a suitable deployment scenario such as in cinemas, where the actuation mechanism could be placed underneath the seats arm rest. We look forward to inspiring other more practical implementations in the future.

Sensing: The same paradigm of actuation can be adapted for sensing. By placing magnets on the hair such as Neodymium powder, the hair deformation could be measured with magnetic sensors. In turn, the hair deformation could infer physiological or external environmental conditions such as wind, temperature, gestures, etc.

Facilitating Research in Affective Touch: Inspired by the results in the formative study, M-Hair, by generating a non contact tactile sensation that specifically targets the hair, offers an alternative actuation mechanism as a research tool for future research in affective touch. For example, pleasure [16, 20, 24], sense of safety, comfort, and pain relief [19], mediation of erotic tactile stimulation [12], and therapies such as for Anorexia Nervosa, where affective touch has proved to be helpful [4].

CONCLUSION

M-Hair is a first step towards a larger vision of augmenting human body with passive add-ons, such as cosmetics. The current work presents a novel way of creating tactile feedback by stimulating only the body hair. With a proof-of-concept setup, we investigated the viability of the actuation mechanism and suggested possible applications in the field of affective touch. Future work needs to focus on developing more practical materials, instruments, and workflows to present such a novel feedback.

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