MAGHair: A Wearable System to Create Unique Tactile Feedback by Stimulating Only the Body Hair

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Figure 1: a) Twenty samples of hairs after applying a magnetic cosmetic recipe, b) Bottom view of the wearable prototype with the permanent magnet on it, c) Wearable device on the forearm, d) view of the device from the bottom while actuating the augmented body hair.

ABSTRACT

We present MAGHair, a novel wearable technique that provides subtle haptic sensation by stimulating the body hair without touching the skin. Our approach builds on previous research in magnetic hair stimulation and magnetic locomotion. We use magnetic cosmetics to augment the body hair, which can then be stimulated by a wearable apparatus that combines electromagnets and permanent magnets. We provide technical insights on the implementation of a fully functional wrist-worn form factor and early adaptations into other form factors. In addition, we provide a workflow for evaluating and characterizing the magnetic cosmetic recipes. Finally, we evaluate MAGHair, which demonstrated that users could detect the sensation of hair movement that they described as gentle and unique.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; User studies.

KEYWORDS

Mobile Haptics; Hair; Hair interfaces; Non-contact Tactile Stimulation; Magnetic Actuation; Magnetic cosmetics.

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1 INTRODUCTION

Human skin is comprised of different mechanoreceptors that respond to different haptic stimuli, such as temperature or pressure [22]. Haptic interfaces stimulate these mechanoreceptors to transmit information to the user, such as notifications, alerts, etc. Apart from warmth and protection, human hair also has a significant role as a sensory organ. Glabrous skin is innervated by mechanoreceptors sensitive to deformation, vibration, and slippage. However, human hairy skin is richly innervated with C tactile afferents, which are a highly sensitive type of neuron [17]. The C tactile afferents are found to be related to pleasant touch [10, 16], and to mediate pain [19].

Previous research [4] explored the usage of body hair as a haptic interface. Their approach consisted of augmenting the hair with a mix of off-the-shelf cosmetics and then stimulating these ones with a permanent magnet attached to the head of a large moving 2D plotter. Later work showed how this haptic stimulation could improve media experiences, such as VR [3]. However, it presents substantial limitations due to the form factor, which is bulky and not wearable, restricting user movement while the stimuli are being generated. Our work explores ways to overcome these challenges by creating a wearable that can provide a similar sensation.

In MAGHair, our approach relies on magnetic locomotion techniques to stimulate the body hair. We combine the usage of electromagnets and permanent magnets to move a strong magnetic field that attracts and stimulates the magnetized skin hair. The magnetizing of the body hair is done by applying magnetic cosmetics, which are high in ferromagnetic particles. With this technique, we are able to control a large magnetic field (76mT at 10mm from the source) with a movement precision higher than 2mm while keeping a wearable form factor and reduce other unwanted vibrations. This was built into a wrist-worn form factor and evaluated with 10 participants. The results evidenced that MAGHair provides a gentle touch sensation that participants described as windy and pleasant. We also present a customized magnetic recipe, where we evaluate and characterize the response of the hair to magnetic fields. Our proposed recipe shows a significant improvement than the off-the-shelf cosmetics used in previous research [4].

In summary, our contributions include:

- A workflow for creating and testing ferromagnetic recipes to augment skin hair that can be actuated with changing magnetic fields.
- A technique to stimulate the augmented skin hair, using a combination of electromagnets and permanent magnets that can be embedded into a wearable form factor.

2 RELATED WORK

2.1 Affective Touch

Haptic technologies often target various mechanoreceptors in the skin using thermal, electrical, and mechanical stimulations. For example, the skin's mechanoreceptors easily perceive vibration, skin stretch and deformation, and relative tangential movement on the skin's surface at the finer spatial resolution, compared to thermal and electrotactile stimulation [6]. Research has shown that we have a specific neurophysiological system that mediates the affective rather than the discriminative properties of touch [21, 24]. This system comprises of C tactile afferent (CT afferent), which is a type of slow-conducting, unmyelinated, mechanosensitive peripheral nerve fiber, with gentle stroking being the best method for stimulation. CT afferents are found only in hairy skin and not in glabrous skin. So far, the most used methodology to generate this gentle stroking is through the usage of a mechanized brush [21]. Its stimulation forces range from 32.5mN [1] at velocities of 120cm/sec [20]. However, this technique requires complex mechanical precision. Our work builds on recent research by Boldu et al. [4], who proposed an alternative approach of simulating the hair with magnetic fields.

2.2 Body Hair stimulation

Related work on hair stimulation presents two different methodologies on how to stimulate the body hair. Fukushima et al. [8, 9], presents a technique on actuating the body hair through the usage of electrostatics. It hovers an electrode, charged at 20kV, over the forearm hair, while the forearm is connected to the ground. This voltage difference makes the body hair attracted to the electrode, which is perceived by the users. With this approach, the authors built a chair [8] with electrodes to generate a stimulus on the forearm. The chair was then used to improve audio-visual entertainment and enhance the feeling of surprise. However, the authors applied the sensation to the overall forearm surface instead of a specific area. Another approach that gives a more focused stimulation is the one used by Boldu et al. in M-Hair [3, 4]. The authors augment the body hair with off-the-shelf ferromagnetic cosmetics to attract the hair from a certain distance with magnetic fields. They are capable of generating a stimulus at a speed of 3cm/s, which previous research in affective touch states as potentially optimal in stimulating CT afferents [20] by using a modified 2D plotter. This solution was then evaluated with virtual reality content [3], which reportedly improved the immersion on the virtual content. Although the VR experience improved, the bulky form factor presented a substantial limitation. The user must remain static while using the system, limiting the media experience, such as interacting in a virtual reality environment. In MAGHair, we present a novel approach of combining permanent magnets and electromagnets that enables the system to control a strong magnetic field while maintaining a wearable form factor. This approach can then be used to support interactions on different form factors.

2.3 Smart Cosmetics

Duo Skin [14], multi-touch skin [23], skin marks [32] and Tacttoo [34] are examples of HCI research that augmented the skin to enable interactions with the environment. However, placing electronics on the skin still faces challenges in safety and degradation, due to the complexity in designing and manufacturing materials and components that are electronically robust and safe for the human skin. HCI research explored the possibility of using cosmetics to augment the skin for interaction purposes [13, 31]. Cosmetics have long existed in society for beauty purposes and, therefore, considered socially accepted. Earth tones [13] proposed a set of cosmetic recipes that changes colour to visualise environmental factors. L'Oreal proposed makeup that changes colour based on the duration of exposure to UV radiation. Emerging research focuses on the potential of applying cosmetics to the body hair for HCI proposes. Boldu et al. presented magnetic cosmetics [4], which are cosmetics that have a high concentration of ferromagnetic particles and, thus, reactive to magnetic fields. These cosmetics were obtained through mixing off-the-shelf cosmetics, which had a low concentration of ferromagnetic particles, and the researchers did not report the characteristics of the recipe. In MAGHair, we propose a new workflow of creating and evaluating passive magnetic cosmetics that can be used to augment the hair to respond to magnetic fields as well as a new methodology to characterize the strength (°/mT) and homogeneity.

3 MAGHAIR CONCEPT

MAGHair proposes a wearable approach to stimulating the body hair without touching the skin. Non-touch stimulation is achieved by applying cosmetics, such as gel or wax, with a high concentration of ferromagnetic particles, to the body hair, and actuating them through strong magnetic fields. A battery-powered wearable device controls the magnetic fields. The design of MAGHair addresses two aspects: (1) overcome the form factor limitations evident in previous work [4], and (2) create a methodology to develop, evaluate, and characterize magnetic cosmetics that are safe, easy to apply, and have good ferromagnetic properties. The design of MAGHair needs to account for the following considerations:

Haptic Sensation: The designed system should generate a subtle, gentle haptic sensation. To achieve such a sensation in a wearable form factor, we focused on targeting the hair follicles, inspired by previous research [4, 8]. The overall feeling should relate to affective touch presented in previous research [21, 24]. Based on this, the system should stimulate the hair with a stroking motion at speed between 110cm/sec, instead of a motionless variable-strength magnetic field [20].

Wearable Form Factor: The system should have as few moving parts as possible to enable easy manufacturing and a small modular form factor, allowing it to be embedded into different wearable form factors. Ideally, the system should consume as little energy as possible and be powered by a small battery.

Augmentation of skin hair: This should be done by applying a substance made out of commonly used cosmetic materials, providing homogeneous properties, be durable, and enable easy application. The used recipes should be practical, safe, and replaceable. Also, the recipe should have strong ferromagnetic properties and be durable for a long period of time.

Safety: Although it is generally safe for the human body to be around magnetic fields, it is important to be cautious while magnetic fields rapidly change near the human body [7, 26], since they can induce currents. In MAGHair, the magnetic fields target relatively low speeds of 110cm/sec and are below 300mT (milliteslas). Also, the applied cosmetics should use materials commercially approved for cosmetic use.

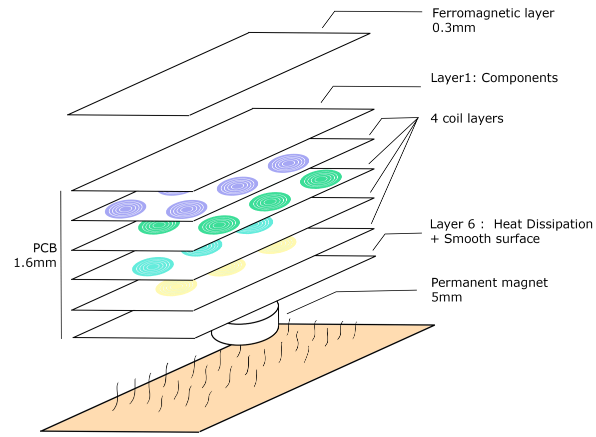

Figure 2: Overall structure of MAGHair. Top: Ferromagnetic sheets made of silicone and Fe (99%) that attract and hold the permanent magnet. Middle: 6-layer PCB with micro-coils that control the permanent magnet. Bottom: Neodymium permanent magnet that attracts the body hair and generates a haptic stimuli without touching the skin.

4 TECHNICAL IMPLEMENTATION

4.1 Design of Magnetic Fields

Magnetic Field Strength: To stimulate the magnetic hair, it is necessary to generate a magnetic field of about 30mT per degree of hair bending angle (see the "Magnetic Cosmetic Design" section). The deformation (°/mT) of the hair depends on the used recipe (see Figure 6). This magnetic field is quite strong and thus not easy to generate and control through a purely electromagnetic approach based on Maxwell's equation $B=\mu nI$, where μ is the permeability of the core, n the coil turn density, and I the current. A purely coil-based approach requires high current and a high number of turns to generate a strong magnetic field. High current implies challenges in dissipating the heat generated. It also makes it impractical to power the device through a battery. A high number of turns of the coils is not feasible since it requires a larger coil area, which decreases the resolution of the 2D magnetic field control and increases the construction difficulty. Therefore, we decided to use a Neodymium permanent magnet as the source of the magnetic field.

Magnetic Field Control: Previous research used a modified 2D plotter to precisely control a permanent magnet [4]. However, the setup was not wearable. Initially, we attempted to control the Neodymium magnet with mechanical actuators such as servomotors. However, we observed that when moving the actuator at 3cm/s, the actuators generated undesirable vibrations. Inspired by magnetic locomotion techniques [30, 33], which were used in Micro-robot Swarms [5] and Re-configurable Tactile Elements (RTE) [27–29], we developed a technique to precisely control the 2D motion of the Neodymium permanent magnet, while keeping a wearable form factor. PCB coils are designed and integrated into the inner layers of a 6-layer PCB (layers 2, 3, 4, 5) (see Figure 2). To have fine control over the permanent magnet and generate linear and complex movements, we used small coils. Each coil is implemented in one internal layer of the PCB and has an overall size of 15mm×15mm and 15 turns. We designed the coils with 20% overlap to ensure a smooth transition between coils. The selected shape for the coils was round (see Figure 2). With this, we are able to generate composite small magnetic fields ("seeds") that attract the permanent magnet to the desired location and, thus, present a strong magnetic field in a certain location.

Coil Design: To achieve a 2D movement of the magnetic field, we generate a composed magnetic field with up to 4 different coils simultaneously. This creates intermediate attraction points, enabling the system to move the permanent magnet smoothly, thus reducing the overall vibration (see Figure 3). The size of the coil, together with the trace, and the number of layers of the PCB, defines the impedance of each coil, the current that will go through at a certain voltage, and the magnetic field that will be generated. The magnetic field is proportional to the number of turns. We attempted to maximize the number of turns during our design. We used FEMM[1] to simulate the magnetic field generated by the coils, as well as the permanent magnet. To embed as many loops as possible in each coil and maintain manufacturing affordability, we decided to use a 6-layer PCB with 6mil traces where the coils had 15 turns. Each coil presented 1.85Ω of impedance, which will then define the maximum current of 1.8A per coil when powered by a 3.7V battery. The magnetic field of the coils can be approximated as a cone [18] that changes its strength based on the current. In our case, when the system drains current of 1A through a 15-turn coil, it generates a magnetic field of 1.2mT at the coil's surface.

Permanent Magnet: The selection of the permanent magnet affects the overall performance of the system, as well as the overall size of the wearable. The bigger the size of the magnet, the higher the magnetic field, and the stronger the force attracting the magnetized body hairs. However, the weight of the magnet is proportional to the size. The larger it is, the heavier it becomes, and the harder it is to control, which reduces the system's precision and requires more power to operate. The main reason for this phenomenon is the increment of the momentum of the permanent magnet, as well

[1] http://www.femm.info

Figure 3: Conceptual schematic representing the overall PCB design of MAGHair. Example of how PWM signals can generate a composed magnetic field that will attract the magnet in between both of them.

as the friction with the PCB surface. Furthermore, the larger the permanent magnet is, the more distributed the overall magnetic field is, which results in a larger area of body hair stimulated. However, the haptic sensation perceived by the users is the motion of the magnetic field. Therefore, the precision of the magnet is the same, just a larger actuation surface. For control purposes and to ensure a smooth motion of the permanent magnet between coils, we want it to be touching at all times with at least 4 coils (see Figure 3). Therefore, based on our coil design, the permanent magnet needs to have a diameter larger than 10mm. The grade of the Neodymium magnet also has a considerable effect on the strength of the magnetic field and its working temperature. The higher the grade, the stronger the magnetic field. In our case, we used N45 due to limitations on our local supplier. N45 is one of the middle-range grades. A higher grade permanent magnet, e.g. N52, could increase the magnetic field by over 10%. Considering all these parameters and after some prototyping and performance evaluation (see section "System Performance"), we decided on a round-shaped permanent magnet [2] with a diameter of 16mm and thickness of 5mm.

4.2 Holding Mechanism

To maximise the strength of the magnetic field and thus the sensation, we decided to place the permanent magnet as close to the user's hair as possible, but without touching the skin, i.e., the magnet hovered above the skin. However, the problem of placing the magnet upside down is that MAGHair needs to continuously fight against gravity. To keep the permanent magnet afloat while not draining energy, we developed a holding mechanism. It consists of multiple thin ferromagnetic layers, placed on top of the electronics, on the opposite side of the permanent magnet (see Figure 2). These ferromagnetic layers attract the magnet and so balance out the weight of the magnet. Each of the magnetic sheets was made by mixing silicone and iron particles (Fe 99%) and applying them to a water-transferable sheet. By changing the proportions of the mixture, as well as the thickness of the sheet, we can change the magnetic attraction force. The silicone-to-iron ratio of the used mixture was 2:3. The mixing was done with a centrifugal mixer[3] for two 3-minute rounds at 2000rpm. The mixture was then applied on a transfer paper at a thickness of 200μm. The sheets were then easily cut into the desired shape and glued to the PCB surface. In our case, to hold the 16mm wide and 5mm thick Neodymium N45 magnet, we stacked 3 such sheets placed at a distance of 3mm from the magnet. Instead of using multiple sheets, it is also possible to design one sheet with the specific amount of ferromagnetic particles to hold the magnet at the desired location.

Figure 4: Reproduction on the used process to fabricate the holding mechanism. Left) researcher pouring a mix of silicone with Fe 99%. Middle) Machine applying a 200μm layer to a transfer paper. Right) Solution before cutting it into the desired shape

4.3 System Integration

Electronics: We created an overall actuation surface of 50mm×60mm, which was populated by a total of 30 micro coils (5 rows & 6 columns) separated 10mm apart from each other. To control all the coils while maintaining a reduced number of components, as well as to make the design modular, we adopted a similar approach used in the previous work [28], which drives the coil in the same way as an LED display (Row-Column). We created a matrix using 5 P-MOS(AO3401A) and 6 N-MOS(AO3400A). Each of the coils had a 2A Schottky diode (MSS2P3) in series, to avoid back current going through the coils (see Figure 3). Each of the MOSFETs was driven by a PWM signal that was generated by a DSPIC33 using an internal oscillator at 100MHz. The magnetic field generated by each coil was controlled by a PWM signal at 21KHz. By changing the duty cycle of the different PWM signals, we were able to control the current drained by each coil, which in turn controlled their magnetic field (see Figure 3). To achieve diagonal movement, we limited the maximum PWM duty cycle at 50% (1A) and used the complimentary to control the other pair of coils (see Figure 3).

[2]https://www.magnets.co.nz/shop/neodymium/discs-and-cylinders-neodymium/16mm-x-5mm-neodymium-disc/

[3]http://www.thinkymixer.net/products/item-all/ce-certified-model/are-250ce.html

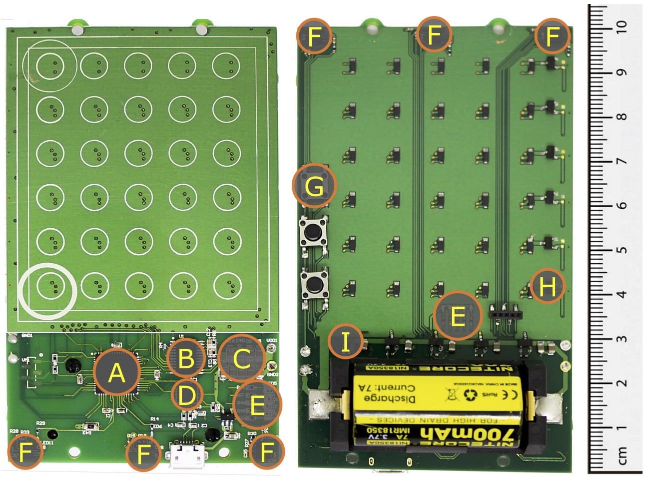

Figure 5: Image of MAGHair PCBs. A) Microcontroller (DSPic33), B) I2C Bridge, C) Battery of capacitors, D) FTDI, E) Debug LEDs, F) Hall Effect Sensors (MEMSIC MMC5883MA), G) Switch Control, H) N-MOS, I) P-MOS

Power Supply: To power the board, we used a Nickel battery 18350. This battery is designed for high drain devices and can discharge currents up to 7A at 3.7V, while keeping a small form factor. As the system is powered at 3.7V, each of the PCB coils presents an impedance of 1.8Ω and the Schottky diode has a VF (forward voltage drop) of 0.47V, we can approximate that the maximum current through one of the coils at any point is about 1.8A. Therefore, MAGHair can continuously drive about 3 coils at maximum power. However, in our case, since we drove the coils at 50% maximum duty cycle, we can drive up to 7 coils at once.

Heat dissipation: The coils dissipate up to 3.6W of energy in the form of heat when current runs through them (1.8Ω×1.8A). With our 6-layer PCB, we allow for faster dissipation by having the top and bottom layer coated with copper (ground planes), as well as internal layers having a large amount of copper coating. With this setup, we were able to use the system over extended periods of time without heating up.

Weight: MAGHair weighs 138g. The heaviest components are the casing (50g) and the battery (50g). As a reference, the weight of a standard smartwatch, such as the Samsung Galaxy Watch 4G is 42g [4].

4.4 System Performance

To better understand how the system works, its performance, and limitations, we evaluated MAGHair with different permanent magnets of different thicknesses and sizes. These were selected from a local store, and the main requirement was to be larger than 10mm in order to be in touch with 4 coils at any time.

Minimum current: was measured using an external power source. The magnet was kept at the centre of one of the coils, while the adjacent coil increased the PWM duty cycle step by step, starting from 0. Once the magnet started to move, the researcher captured the current value. We clarify that the reported current is the overall current of the system while using 1 coil, without considering the voltage drop of the transistors. The microcontroller and the peripheries (sensors, FTDI, etc.) have a power consumption of about 58mA.

Maximum speed: was calculated by moving the permanent magnet at full power. We performed 100 movements in each of the vertical and horizontal directions. Each movement consisted of 8 steps; each of them had a 10mm size, with 4 in each direction back and forth. We then calculated the average of the vertical and horizontal speeds.

Movement precision: was calculated by moving the permanent magnet slowly step-by-step from one coil to another. Each step was made using the technique previously described (see Figure 3). Since the distance between the two coils is 10mm, we calculated the precision of the movement as 10mm / number of steps.

Magnetic field: was calculated using a hall effect sensor (MAG3110) at a distance of 30mm from the surface of the Neodymium magnet.

Table 1: System Performance Results based on the usage of different permanent magnets

	Size (mm)	Volume (mm^3)	Current (mA)	Max Speed (cm/s)	Precission ($\pm mm$)	Magnetic field (mT)
	16 x 5	1005	170	10.15	1.67	1.65
	12 x 12 x 12	1728	750	11.36	3.33	2.47
	12x7	758	430	12.91	3.33	1.06

The results are shown in Table 1. Based on these results, we confirmed that the permanent magnet we selected for the design (16mm diameter × 5mm thickness) is a good choice based on the lower current, higher precision, speed (10.2cm/s) and magnetic field strength of 1.7mT at 30mm.

4.5 Challenges

The main difficulty in the design and development of MAGHair is to match the large magnetic field needed to stimulate the hair (permanent magnet) and the strength of the magnetic field generated by the coils used to control and move the permanent magnet. To move a larger permanent magnetic field, we need higher currents, as shown in the previous description and evaluation.

The size of the permanent magnet also affects the design of the holding mechanism, which has to be adjusted for each of the different actuators. With the presence of stronger magnetic fields, the fabrication process of the holding mechanism needs to be more precise. A holding mechanism that is too strong will create excess friction, and a weak one will not hold the permanent magnet properly. Furthermore, when the user makes sudden movements with large accelerations, the permanent magnet may detach from the holding mechanism. This can be improved by actively generating a magnetic field that holds the magnet. However, an active holding of the permanent magnet induces higher power consumption.

[4]https://www.samsung.com/nz/wearables/galaxy-watch-r815-42mm-4g/SM-R815FZDAXNZ/#specs

The current needed for the system (1.8A) generates heat that needs to be dissipated. If the system heats, the permanent magnet will also heat up. The temperature affects the magnetic field characteristics of the permanent magnet, and the overall performance of the system. In the case of the selected permanent magnet, Neodymium grade N45, the manufacture states that the performance will decrease when the magnet exceeds 80°. Throughout the design of the PCB, we already enabled a steady passive dissipation. We dedicated 2 layers of the 6 layer PCB mainly for heat dissipation by pouring large areas of copper planes (see Figure 5).

5 MAGNETIC COSMETICS DESIGN

Previous research in magnetic hair stimulation [4] presented a recipe by mixing off-the-shelf cosmetics. However, upon reproducing the recipe, we found that it did not adhere well to the body hair, and it had a low concentration of ferromagnetic particles. In MAGHair, we present two new magnetic recipes that perform significantly better than previous work. Also, we systematically evaluated these recipes in terms of their homogeneity and ferromagnetic properties.

5.1 Recipe Generation

Base Foundation: The purpose of the base foundation is to attach ferromagnetic particles onto skin hair. From the large variety of hair fixer products, we selected gel (VO5 Extreme Style Gel) and wax (Gatsby Moving Rubber Grunge Mat). Both were chosen from a drugstore near the research institute. The choice of gel (dry and straight) or wax (wet and curvy) decided the final look and feel of the augmented hair (see Figure 6).

Ferromagnetic Particles: The purpose of the ferromagnetic particles is to react to magnetic fields and therefore, bend the hair once a magnetic field is close by. The selection of ferromagnetic particles was made based on safety standards and commonly used materials in cosmetics. Inspired by existing current cosmetics, we selected iron (III) oxide (Fe_2O_3), which has been frequently used as colour pigment and has a high ferromagnetic characteristics. Also, we selected a commercially available magnetic facial mask[5], which has high concentrations of iron particles.

Mixing: To mix the base foundation and ferromagnetic particles, we used a centrifugal mixer[6] for 3 3-minute rounds at 2500rpm. The results of the recipes after mixing are shown in Figure 6. All the recipes were mixed with 1:1 weight ratio between ferromagnetic particles and base foundation.

Safety & Regulations: The compositing materials are safe for skin, as relevant regulations suggest [2]. However, regulations differ by country [15]. Iron(III) oxide is largely used and approved by the US Food and Drug Administration (FDA)[7] (when purity requirements are fulfilled) for use in cosmetics for eyes and lips. Also, it has no chemical or physical reaction to acid, alkali, heat, light, moisture, oils, or oxygen, making it an ideal material for cosmetics purposes.

[5]https://www.drbrandtskincare.com/products/magnetight
[6]http://www.thinkymixer.net/products/item-all/ce-certified-model/are-250ce.html
[7]https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?fr=73.2250

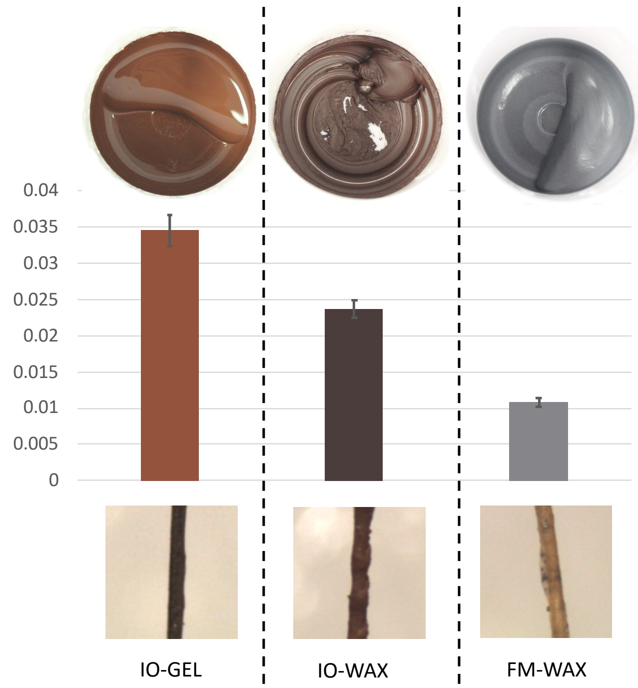

Figure 6: Representative images of the 3 different cosmetics. Top: final appearance of the recipes, Middle: deformation of the hair (°/mT), Bottom: microscope ×100 exploring homogeneity of the hair after applying the recipe.

5.2 Recipe Characterisation

We designed and compared 3 different recipes (see Figure 6 top). Two of them used iron (III) oxide (Fe_2O_3) as ferromagnetic particles and gel (IO-Gel) or wax (IO-Wax), respectively as the base foundation, and the other one used off-the-shelf cosmetic mixed with wax (MF-Wax) as presented in M-Hair [4].

5.2.1 Experiment Setup. To consistently measure the hair bending based on an applied magnetic field, we created an instrumentation setup (see Figure 7). An individual hair was placed between an electromagnet and a hall effect sensor (MAG3110), while a computer microscope (×100) captured the hair movement. The electromagnet, located at a distance of 5mm from the hair, generates 56 different magnetic fields strengths, which attracted the ferromagnetic particles of the recipe and, in turn bent the augmented hair. This bending is based on the strength of the magnetic field and the used recipe. The sensor, placed perpendicular to the hair, measured the strength of the magnetic field in 3 axis. We then approximated and normalised the magnetic field applied to the hair based on the magnetic field attenuation in the air.

Once the researcher placed a hair on the setup, a Python script automated the whole process by generating different magnetic field strengths, capturing an image of the hairs before and after every magnetic field strength. The deflection was measured through a computer vision algorithm, which vectorised the images and extracted the deflection angle before and after (see Figure 7). The results were then exported into an Excel file.

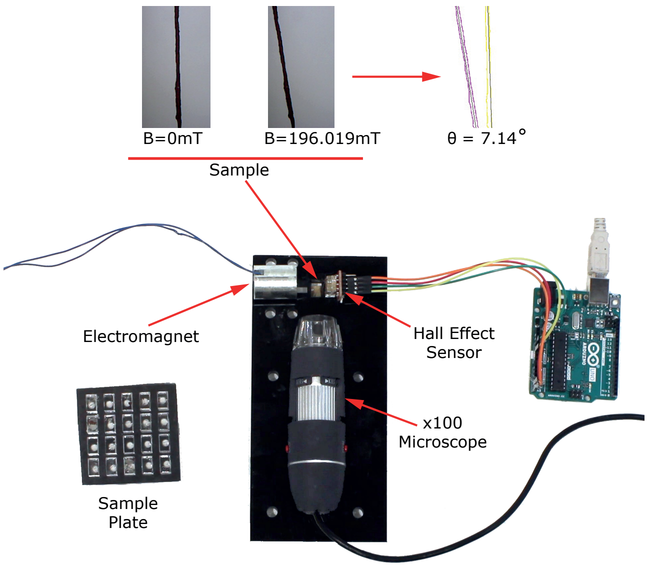

Figure 7: (Bottom:) Image extracted from the instrumentation setup to evaluate and extract hair deflection. (Top:) A real example on how the computer vision algorithm calculated the hair deflection based on applied magnetic field (°/mT).

5.2.2 Procedure. We followed these four steps: (1) Collect individual hair samples as homogeneous as possible. (2) Apply each recipe to 20 different individual hairs with an eyelash brush. (3) Measure the homogeneity of the hair through a microscope. (4) Place the hair under the experiment setup (see Figure 7) and measure the hair deflection based on different magnetic fields strengths.

5.2.3 Results. Hair bending: We measured hair deflection based on the degrees the hair bent after applying a specific magnetic field. We observed a difference in hair deformation (°/mT) for different recipes (see Figure 6). A one-way ANOVA found a significant effect of recipe type on the degree of hair bending ($F(2,3345)=240.4$, $p<.0001$). Tukey HSD post-hoc test confirmed the pairwise significant differences between each of the recipes (all $p<.0001$). Iron(III) oxide, which is commonly used in cosmetics and FDA approved, performed significantly better than the existing facial mask in terms of deformation.

Homogeneity: We defined hair homogeneity based on how well the recipe distributed on the hair. A picture of all 60 hairs was taken with a ×100 microscope (see Figure 6). Two researchers independently rated the homogeneity of each sample from 1 (least homogeneous) to 5 (most homogeneous) using a given template. The results indicated that FM-WAX($M=4.23$, $SD=0.91$) was the most homogeneous recipe, followed by IO-GEL($M=3.46$, $SD=1.27$) and IO-WAX($M=2.71$, $SD=0.75$). A one-way ANOVA found a significant effect of recipe type on the homogeneity ($F(2,3345)=15.40$, $p<.001$). TukeyHSD post-hoc test confirmed the pairwise significant differences between each of the recipes (all $p<.05$).

Ease of application: The application of the recipe to the body hair was done by moving an eyelash brush close to the body hair while spinning it. We observed that the gel-base recipe was easier to apply. The finding aligned with our expectations since a gel recipe is water-based.

6 USER EVALUATION

We conducted a study with ten male participants aged between 19 and 32 years old (M=25.9 SD=3.7) from a university community to understand the sensations that MAGHair generates. Following previous research [4], we target 2 main points: (1) Evaluate if the user can perceive the haptic stimuli and whether it is exclusively generated by the hair movement. (2) Obtain a subjective description of the sensation.

6.1 Setup

Apparatus: The apparatus used for the experiment was the same as described in section "Technical Implementation". However, a few modifications were added to facilitate the user studies. (1) To monitor the power consumption, we connected the device to an external power supply. (2) We added 3 buttons for the experimenter to select the desired actuation pattern, start and stop the actuation. (3) We also added a custom-made VGA(OV7570) micro-camera inside the device together with an LED, allowing the researcher to monitor the performance of the device and the behaviour of the body hairs (see Figure 5).

Recipes: Based on the extracted results from the recipe characterization, we selected IO-GEL (iron (III) oxide with gel). This recipe had the highest hair deflection (°/mT) ratio while keeping a good homogeneity. For the purpose of the experiment, we also developed a placebo recipe made out of red pigment colorant and gel.

6.2 Procedure

The experiment took about 60 minutes per person. To avoid any external interference, participants wore headphones playing white noise. At the beginning of the experiment, the researcher applied the two recipes (placebo and IO-GEL) to the participant, one on each forearm. At the end of the experiment, the participant was given a set of wet baby wipes to clean the cosmetics. Before the experiment, participants completed the information sheet and consent forms, as well as a demographic questionnaire.

The steps followed during the experiment were: (1) The researcher applied two different recipes, one in each participant's forearm. This was balanced between the right and left forearm among the 10 participants. (2) The apparatus was then placed on one of the forearms and produced the stimulus for 30 seconds. (3) Then, the apparatus was placed on the other forearm and produced the stimulus for 30 seconds. (4) The apparatus was removed from the participant. (5) The participant was then asked to rate on a Likert scale (1-5) the strength of the sensation on each of the arms, as well as to describe the perceived differences between both arms. (6) Finally, the participant was asked to provide 1 to 5 words that described the perceived sensations on the arm presented with the actual stimuli.

6.3 Results

Perception: Participants rated on a five-point Likert scale (5 being strongly noticeable and 1 being not noticeable) the sensation on the arm with the recipe as ($M=4.0$, $SD=0.63$) the one which felt significantly stronger (paired samples Wilcoxon signed-rank test:

p<.01) than the one with placebo (M=1.8, SD=0.75). Interestingly, 4 out of the 10 participants reported *"literally don't feel anything"* on the arm that contained placebo, although its sensation is statistically different from "feeling nothing" (one-sample Wilcoxon test against a mean of 1: p<.05). The rest of the participants reported feeling a very minute sensation. One of the participants described the sensation as *"one ant running on left (placebo) and a bunch of ants running on the right (IO-GEL)"*. Post analysis of the recorded videos from the internal camera revealed that in some cases, after applying the placebo recipe, some of the hairs were straight and in contact with the permanent magnet.

Subjective Description: From the 10 participants, we collected a total of 23 different descriptions for the sensation. The most mentioned words were: Touch (Gentle, Subtle) (number of times mentioned N=7), Hair Pulling (N=4), Wind Blowing (N=3), Ticklish (N=3). The participants experienced difficulty with accurately describing the sensation or making analogies to existing experiences. For example, P6, reported that: *"no one has ever pulled my hair like this, but I like it. However, it's hard for me to describe this new sensation"*. Other words reported by the participants only once include: Unique, Soft, Running ants, Stroking, Strong. These results are aligned with the work presented by Boldu et al. [4].

6.4 Discussion

Subjective Description: From the obtained results, we observed that MAGHair generated a pleasant and positive sensation, relatable to gentle and soft touch, as well as hair pulling. Some of the participants also reported difficulties in describing this sensation, given it was the first time they felt this type of sensation. The findings related to results extracted by previous research in Magnetic Hair Stimulation [4], as well as Electrostatic stimulation [8, 9]. However, further evaluation is necessary to better characterize the sensation.

Body Hair: We hypothesise that the different body hair characteristics of the different participants had an overall impact on the perceived sensation. Previous research in affective touch already explored some of these relations between hair type and the perception [12]. During this experiment, we required participants to have enough hair on their arms, which limited our selection of participants to males. However, further research is required to better understand the effect of hair density, quantity, gender, type, length, and race on the MAGHair haptic perception. As shown in future applications, the same technique could be adapted to stimulate other body parts with hair, such as on the head.

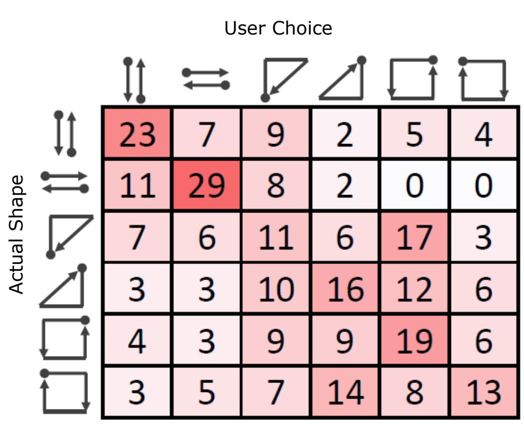

Figure 8: Confusion matrix based on the 6 different patterns stimulated. While vertical and horizontal linear motions can be better differentiated, close loops and their directions are hard to differentiate.

Shape Discrimination: Using a similar approach to previous work [4], we performed a second phase of the experiment with the same participants and evaluated the discriminative sensation generated by MAGHair. We evaluated a total of 6 gestures (see Figure 8). However, instead of asking the users to draw what they perceived [4], we used a "multiple choice" approach, with training on the multiple shapes, following a similar approach to previous work [11]. The results showed a low discriminative sensation, and do not deviate much from previous research evaluating shape discrimination on a forearm [4, 11] Shape discrimination performance might be better when the presented shapes are larger. However, due to the limited form factor of our apparatus, we did not test this hypothesis in our current work.

Cognitive workload: The experiment was conducted without any distractions, apart from the white noise to mask the sound from the system. Future work should evaluate the effect of different cognitive workloads on the stimuli perception by introducing primary tasks requiring user attention and measuring how easily a participant could identify the stimuli.

Binary stimulus: The magnetic field generated by the used Neodymium magnet at a distance of 10 mm can be approximated to 76mT. Based on the previously extracted results from the recipe characterization of IO-GEL, 76mT induces a hair bending of about 2.58° at 10mm away from the magnet. Given the overall actuation, the surface is 50mm×60mm, and the diameter of the magnet is 16mm, we hypothesize that the stimuli are generated to an overall surface area, rather than a focused point. This creates a more subtle sensation to an overall area rather than at a specific point, creating a lower resolution (see Figure 8).

7 WEARABLE APPLICATIONS

The usage of MAGHair as a subtle haptic feedback interface could open up potential applications related to affective touch, such as pleasure, pain relief, or social touch [22], as well as enriched media experiences, such as more immersive AR/VR content [3] or music enhancement [8]. The wearable form factor of MAGHair allowed for adaptation to various devices. We demonstrate a few of such potential adaptations below.

Smartwatch: Wristbands and smartwatches already incorporate haptic interfaces, such as vibration motors, and there has been a growing interest in HCI to add different types of haptic feedback. Examples include air poking [25] or skin dragging [11]. MAGHair could add value to the existing form factor of a watch by adding extra layers and internal coils to the existing PCBs. This will enable these devices to generate a more subtle haptic stimulation. However, power consumption and EMC (Electromagnetic compatibility) are still challenges that need to be addressed. The presented form factor of MAGHair is already designed to be placed on the forearm.

Virtual Reality: An early prototype that uses the same mechanism of MAGHair, was integrated into a Virtual Reality headset (see

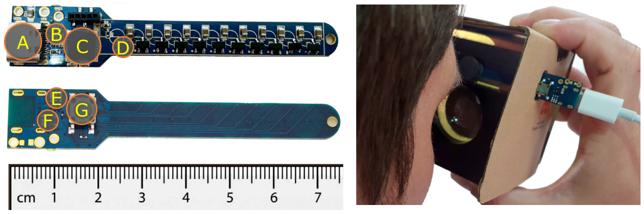

Figure 9: Left) Electronics of the wearable device, A) USB-C to power the board, B) Battery of Capacitors, C) DSPic33, D) P-MOS, F) LDO to power the Microcontroller, E) debug LED, G) Switch Control. Right) Mechanism attached to a google cardboard VR viewer

Figure 9). For miniaturization proposes, we decoupled the battery from the actuation board and connected these two through a USB-C cable. This enabled us to keep a small form factor while being able to drive > 1.8A of current. By placing the actuator and permanent magnet to the inner part of the frame of the VR headset, we are able to deliver a subtle haptic stimulation to the eyebrows of the user. One of the key differences with MAGHair is the angle that the permanent magnet is held and actuated. In the VR headset, the magnet is held at 90 degrees, while in MAGHair is 180 degrees (upside down). As previous research reported [3], haptic hair stimulation can potentially increase the sense of immersion in a virtual reality environment by producing subtle haptic stimulations that represent objects or wind. This adaptation enables this haptic sensation in a mobile environment, such as subtle guidance of the user's attention towards a goal or target.

8 LIMITATIONS AND FUTURE WORK

Holding mechanism: The holding mechanism allows the Neodymium magnet to freely move in an upside-down pose while keeping low friction between the magnet and the PCB. Even though the system worked adequately for the evaluation, we observed some limitations where the magnet fell off when the user moved their arms or performed abrupt gestures, such as shaking. Future research could explore to further increase the holding strength by activating some of the coils to provide extra holding forces. Another solution that future work could explore would be to swap the location of the permanent magnet to the other side of the PCB (i.e., the order would be hair-PCB-magnet instead of hair-magnet-PCB). This will most likely reduce the overall haptic perception but will significantly simplify the design of the holding mechanism.

Actuation Mechanism: The permanent magnets coupled with electromagnets enabled us to control the magnetic field necessary to attract the hair, with a precision of about 2 mm and enabling speeds of up to 12cm/s. This was achieved while keeping a small form factor and powering the system with a battery. Future research could explore using multiple permanent magnets at the same time, as well as exploring other methodologies of generating the needed magnetic field.

Power Consumption: Even though we designed the system to be wearable and battery-powered, it still has some difficulties in a mobile environment. Power consumption is always one of the critical requirements in wearable devices. For the current MAGHair prototype, the average power consumption while generating a stimulation is around 1A at 3.7V while active. This is much larger than the power consumption of a typical vibration motor, which consumes approximately 70mA. MAGHair could drastically improve the power efficiency by a factor of 6, bringing the power consumption down to 150mA. This could be achieved by (1) increasing the number of turns of each coil (e.g. 16 layers PCB or better manufacturing techniques), (2) selecting a smaller and/or higher quality permanent magnet (e.g. N52), and finally, (3) developing recipes with better ferromagnetic properties.

Body Hair: In MAGHair, we elaborated on three different recipes and applied one of them to the forearm of different users. However, different users had a different type of hairs with different characteristics, such as density and length, which are likely to generate a different haptic sensation [12]. We encourage future research to focus on developing similar recipes and applying them to different types of body hair, such as the scalp hair, eyebrows, forearm, etc. to understand the different sensations and implications when applying this haptic stimulus to other body parts. Also, future work could explore the relationship between different hair parameters such as length, density, thickness, with the haptic sensation, and categorize the relation of these parameters to different user groups such as race, gender, and age.

Applications: Previous approaches in hair stimulation lacked wearability. In MAGHair, we introduce a technique to perform hair stimulation in a wearable form factor, as well as evaluate the sensations perceived by the users. We also show some early prototypes of potential wearable devices that could integrate these types of haptic mechanism. We now envision future work to use this technology and further explore the usage of this haptic mechanism in the real environment, such as Virtual and Mixed Reality [3, 8], notifications or guidance towards a target or goal.

9 CONCLUSION

With MAGHair, we presented a novel technique that enables skin hair stimulation in a wearable form factor, using a combination of electromagnets together with a permanent magnet. MAGHair generates subtle stimulus that was perceived as gentle and unique, similar to previous research in hair stimulation [3, 4]. In addition, we presented customized magnetic recipes to augment body hair, as well as a methodology on how to evaluate and characterize their homogeneity and response to magnetic fields. Finally, we discuss how to adapt this technique to different form factors and for different potential applications.

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