CyberHaptics– Magnetic Implants as Haptic Devices

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Abstract—Haptic displays are multiple and diverse in technology. They can be found in the form of fixed, movable, portable, wearable, encounter-type and can display a subset of known haptic modalities. In this paper, we introduce a new category: human implant haptics. Implantable haptics conceptualizes the idea that haptic display systems can also be considered as permanent biocompatible implants in living organisms having touch sensing capabilities. They can be used to display haptic data or enhance perceptual modalities using surrounding nerf-endings. We specifically exemplify and investigate thus new concept, we termed cyberhaptics, with subcutaneous magnetic vibrator implants, and show how they can be used to convey haptic data or substituting non-haptic data into haptics.

Index Terms—Cyborg haptics, subcutaneous magnets, implant haptic displays.

1 Introduction

CYBERHAPTICS, a name composed from cybernetic or cyborg and haptics, designate any technology that enables providing of enhancing human haptics by implanting an artificial component of technology in a living organism. This type of haptic technology is not researched despite potential needs in terms of restoring human haptic sensations for amputees, and the new trend in human augmentation through various technologies (e.g. Google glass, mobile phones, etc.). Almost all existing haptic technologies are external devices that convey haptic data through direct contact on organism's skins. They can be found in the form of fixed or portable, graspable, wearable, touchable (encounter-type), pseudo-type and can display a subset of known haptic modalities, see recent reviews in [?].

It is however possible to envision haptic devices as biocompatible fully or partially implantable devices that are permanently part of the human body. This novel research in cyborg haptics, that we named *cyberhaptic technology* might offer tremendous perspectives and challenging investigations for new knowledge and applications. We are all cyborgs already as we relay and depends on several devices that enhance our perceptual, cognitive and strength capabilities. For being active by essence, haptic devices cannot be fully implantable as they still depend on an external source of information to be displayed. However, the mechanical transducer can be fully integrated and in various ways. In the future, we may expect advances in technology such that more sophisticated implants at different subcutaneous levels can serve the purpose of haptic displays to relay stealthily information.

In this paper, we investigate the use of magnetic implants (see Section 3). Magnetic implants appeared... expliquer l'origine des implants et pourquoi ils sont biocompatible, etc.

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2 Background

2.1 The touch sense and cutaneous mechanoreceptors

In [?] K. Johnson analyzes the four mechanoreceptive afferent neuron types and their distinct perceptual functions in glabrous skin: The Pacinian are located in the deeper layers of the skin and are targeted at sensing fine surface detail as well as vibration and are therefore most sensitive to higher frequencies (> 250 Hz).Rapidly Adapting afferents end in Meissner receptors which are targeted at roughly textured surfaces and therefore are most sensitive to lower frequencies ($30 - 50$ Hz). Slowly Adapting type 1 end in Merkel disk receptors which are situated in the epidermis (superficial layers of the skin). They are sensitive to rough textures, shapes and edges and therefore deformation of the skin. Finally Slowly Adapting type 2 afferents are thought to end in Riffini receptors that are not well understood but most probably respond to stretch.

2.2 Haptic feedback and artificial tactile stimuli

When it comes to producing a tactile feedback many techniques have been proposed and used as seen in [?]. Nevertheless there are two main drawbacks we can see to most of the currently used systems: They involve a direct physical contact between the user (usually the finger tips) and the system, i.e. a device has to be worn, touched or held. Secondly the feedback devices usually involve more or less complex mechanical systems (With the exception of electrotactile stimulation [?]). In addition to the added complexity, mechanical systems face the issue of miniaturization and the difficulty to embrace the uneven nature of the human skin. Nevertheless the more recent approach of using ultrasound interference to produce a stimuli on skin in mid-air [?] solves these issues and makes it possible to produce the sensation of 3D shapes in empty space [?]. We can also mention the air-jet technique although it's much less versatile compared to ultrasound [?]. Still, the ultrasound technique has its own limitations: The stimulation range is limited to tens of centimeters [?]. Ultrasounds do affect the human body and the haptic devices exceed the recommended 110 dB for continuous exposure. They are safe as long as the head is kept at a normal distance from the device [?] but this seems like an issue for both children and animals. Finally the technology requires advanced hand tracking and uses ultrasound waves meaning that any obstruction, either external or by the users body, will disrupt the feedback.

3 Implants for Haptic Rendering

3.1 The touch sense and cutaneous mechanoreceptors

So far, haptic rendering is facing the main issue of practicality. Even in the most advanced implementations the user is either constrained in their movement or ability to use their hands in other ways. This drawback makes haptics unfit for regular or continuous usage in everyday life. To solve this we propose integrating technology directly to the body. This might sound dangerous and intrusive but as we see in this paper it can be extremely simple both from an engineering and a medical point of view.

Implants are not a novel concept and have been used extensively for decades in the medical field. Surprisingly though implant technology is rarely considered outside of the medical realm and has only recently gained in popularity in both aesthetics and the biohacking community. Indeed the type of implant we're interested in comes from said biohacking community and we believe has potential in haptics and human-machine interaction with relatively low risk and invasiveness.

3.2 Subdermal magnetic implants, SMIs

In the biohacking and body-modification communities magnetic implants have existed since the early 2000s. Their main appeal is that they give the implantee the ability to ”touch” magnetic fields, although other uses exist, like integrated headphones with ear implants [?].

3.2.1 Implant design

The implant being placed under the skin it must of course be small. The second criterion influencing the chosen dimension is the influence of the mass of an object on the quantity of energy necessary to move it. In fact, the smaller a magnet (and therefore less massive) the more easily it will be moved by low intensity fields and higher frequencies.

As the implant is placed in a delicate environment, it is preferable to avoid sharp edges and corners in order to avoid any pinching or friction with the surrounding anatomy. However its movement(i.e. rotation) must be able to cause a deformation of the surrounding tissues definitively eliminating the sphere. Usually a disc shape is chosen, with a pole on each face. The M31 (3mm by 1mm disc) has become a standard because it is easily available on the market. The impact of a field on the magnet is also defined by the strength of the magnet itself. For this application we therefore use the strongest type of permanent magnet available, neodymium N52. Neodymium (like most materials) is unfortunately not bio-compatible and requires a coating. This is the main challenge in the design of SMIs because the non-magnetic mass to total mass ratio must at all costs be minimized in order to optimize the system. The coating must therefore be as thin as possible while guaranteeing a decent durability in vivo and a very low permeability. With current manufacturing constraints, the most common options are as follows: silicone, glass, titanium and parylene. Each one with inherent advantages and disadvantages. With a growing demand it seems that titanium encasing is finally becoming affordable for manufacturers and is the most popular option as of 2021 although prices are still high when compared to it's predecessors.

3.2.2 Choice of location and implantation procedure

In order to optimize the sensing, the implant must be placed in an area with a high density of sensory nerve endings. It turns out that the area of the human body with the highest density is the hand especially the fingertips which are also quite convenient for this use.

Initially this type of implant was placed in the tip of the finger opposite the nail as can be seen in [?]. However, practices have since evolved and nowadays we prefer the side of the finger pad so as to avoid daily inconvenience (pinching the implant between the bone and a held object). The installation operation is relatively short and not very intrusive because it is superficial. First a small incision is made on the side of the finger then using a flat tool the skin is lifted so as to form a pocket a little larger than the size of the implant. The implant is slipped into it and an optional stitch can be made.

Under good circumstances the finger can be used normally again after a week. However, encapsulation (reconstruction of the tissues around the implant) can take 3 to 6 months and is not superficially noticeable. It is only at the end of this period that the implant will produce consistent final results. So any experimental measurement within this period should therefore be considered with caution as it might not reflect the actual performance when healed completely.

3.3 Artificially stimulating an SMI

Stimulation is done by creating a magnetic field around the implant. For this we use one or more electromagnets. It is then possible to vary the following parameters in order to vary the feedback:

- The strength or amplitude of the signal.
- The type of signal: sine, square, audio...
- The frequency, for periodic signals.
- The field's shape.

These variations allow information to be communicated to the user through the signal. The information can be spatial because the magnetic field is continuous in space and the user can touch it and explore its shape.

3.4 Sensitivity and frequency range

In this first article on the subject of magnetic implants [?] Hameed et al. establish the concept of sub-dermal magnetic

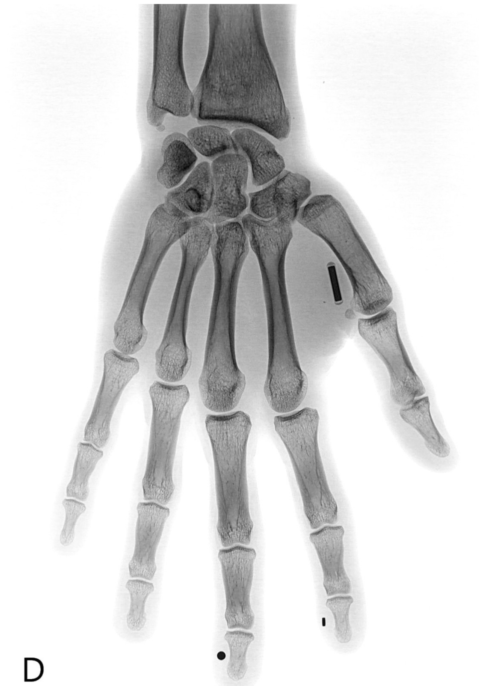

Fig. 1. X-Ray of Axel's right hand (16/10/1019) showing the two identical finger SMIs and a larger glass-encased magnet between the thumb and the index.

Fig. 2. Side-view X-Ray of Axel's 2 finger SMIs (16/10/1019).

implants as well as some properties such as field strength sensitivity and frequency sensitivity. Although there were only two participants in the study it effectively demonstrates the principle of stimulating an implant through an external coil and gives us an idea of the results to be expected.

In a following paper [?] Harrison I. et al. proceed to compare these magnetic implants to surface mounted implants in tests involving amplitude detection, amplitude discrimination, frequency discrimination, temporal discrimination and temporal gap detection. They demonstrated an

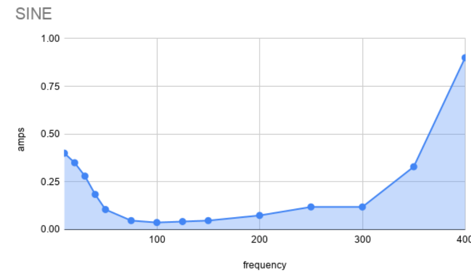

Fig. 3. Relative sensitivity to a sine wave over a 10-400Hz frequency range.

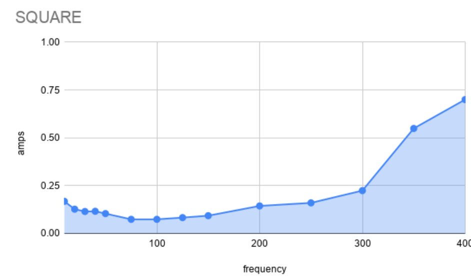

Fig. 4. Relative sensitivity to a square wave over a 10-400Hz frequency range.

advantageous increase in sensitivity for SMIs and a much finer sensitivity on lower frequencies (20-50Hz). They also discovered a lessened frequency discrimination on frequencies higher than 100Hz possibly due to the overlap of sensed frequency ranges between Meissner and Pacinian corpuscles.

A possible omission in both papers on SMIs [?] [?] is the importance of the implant's design (magnet-to-coating ratio, mass and shape) for the sensitivity in higher frequencies or lower amplitudes. In both cases the magnets used are common 1mm by 3mm disk implants that are made this way due to coating procedures and cost limitations. As magnet manufacturing evolves and implantables become more common SMIs are prone to evolve too, improving their performance.

[TO BE VERIFIED WITH OTHER IMPLANTEES] In fact in our tests on more modern implants we found some notable differences. The tests were done in a similar manner using a Kramer PA-240Z amplifier and a coil. A Hirst Magnetics GM07 gaussmeter was used for the magnetic flux measurements. For a reliable detection at 200Hz we measured a threshold lower than 0.005mT as opposed to about 0.03mT in [?]. The large difference can be explained by the upgraded implants (grade N52 instead of N48 and parylene coating rather than silicone) but also by the fact that our results were measured rather than approximated. Also we could not get more precision on the threshold as we were reaching the instrument's resolution limits.

We also were interested in sensitivity over a larger range of frequencies and signals. Again testing in similar conditions we ended up with three different sensitivity curves for a sine, square and sawtooth signal.

As you can see used current as an indicator of sensitivity.

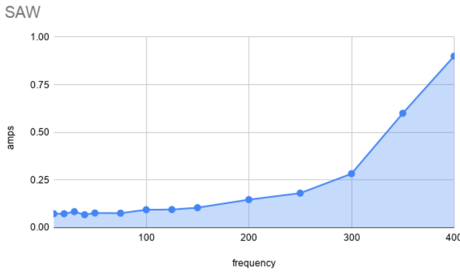

Fig. 5. Relative sensitivity to a sawtooth wave over a 10-400Hz frequency range.

In the following estimation of the field strength $B = \mu n I$ both μ (permeability) and n (turn density) remain constant so the current I is proportional to the field strength B. Since we can easily and accurately measure I we can therefore use it here as an indicator of sensitivity and the vertical axis is effectively the value in amps necessary to reach the threshold with an identical setup.

The results are visibly different for each signal. The most sensitive range overall being 50-300Hz as expected. Also all signals lose sensitivity rapidly over 300Hz. On low frequencies (¡100Hz) the sharp polarity changes in the square and saw waves make them stand out more while the sine wave tends to fade out. This makes sense, in lower frequencies the sharp drops in the saw wave produce a fast change in polarity that can be assimilated to a pulse signal and be felt more easily even in very low frequencies. In the mid-range (100-300Hz), the sensitivity threshold is similar for all waves. Above 300Hz we can see that the square wave does not fade as quickly as the other two. As the frequencies get higher above 300Hz the changes in polarity become too close to be sensed. We can see that the square wave is slightly less affected. It is difficult to explain but we can suppose that the square wave (and saw to some extent) should be felt better in the higher frequencies as the changes in polarity are further apart and sharper. The reason saw waves are less sensitive than square waves in high frequencies might be that the sharp polarity change is always in the same direction and contrary to low frequencies the implant does not get enough time and/or energy to move all the way back. In [?] amplitude detection was only tested on two frequencies, here we test them over a range. Nevertheless the higher sensitivity at 200Hz than 20Hz (Amplitude RL results, sine) is similar in our results.

As tested and proven in [?] tactile stimuli also has the advantage of producing much faster response times than its visual and audio counterparts with no significant influence from the position of the stimuli.

Describing the sensations produced by the stimulation is very subjective but a general idea can be given. As such we have categorized the sensations:

Incoherent	I	Hard to recognize the signal. Noise or a continuous signal with spikes in amplitude. Like holding a bee.
Continuous	C	Feels like lightly sliding the finger across smooth fabric or very soft fur.
Vibration	V	A soft vibration of discernible frequency, not very localized and fades throughout the finger. Can feel like rough fabric.
Buzz	B	A sharp vibration that reverberates through the bone. A pull on the magnet's area can be felt at the same time. Feels like touching a running engine or running your fingers against the bars of a fence.
Tapping	T	A sensation of being hit or tapped at the implant's location at a speed equivalent to the frequency used.
Deformation	D	Feels like something is crawling under the skin, similar to rubbing the finger on a surface of small beads or pressing on a small ball bearing.
Pull	P	Very localized feeling of the implant being attracted in a direction (the direction can be hard to determine). It is a continuous version of ”Tapping” but the mechanoreceptors get used to it so quickly that it takes a lot of power to be felt reliably.

The order they are in loosely correlates to the frequencies they correspond to with very high frequencies tending towards I and low ones towards P but over all different signals tend to intensify different sensations. For example a sawtooth wave will produce a very distinct T while a sine will be much closer to a D. It is also important to mention that depending on both signal type and frequency each of these sensations can feel sharper or smoother while still belonging to the same category. Effectively making it possible to differentiate one signal type from another even though the produced sensations are similarly named.

3.5 SMI key benefits and drawbacks for haptic rendering

By comparing to existing methods we can deduce the strengths and flaws of our implant-based technique. Of course we take into account the constraint of having to have one or more implants placed. However, in view of the trends [?] and the potential of body hacking we will remain optimistic about a future where (non-medical) implants are widespread and accepted.

Benefits:

- As with the ultrasound method, our technique does not require direct physical contact to the stimulated area of skin.
- Our method allows higher and finer force feedback (as opposed to the weaker ultrasound feedback).
- The system is mechanically simple and therefore compact, versatile and scale-able.
- Magnetic fields are unobstructed by the vast majority of bodies and materials (again as opposed to ultra-

sound). They are also not noticeable by humans and the majority of living beings.

Drawbacks:

- SMIs only stimulate at one point (each), therefore we do not have the resolution of a mechanical system or the ability to cover an area like the ultrasound-based system.
- The range of a magnetic field is limited. A magnetic field follows the inverse cube law (R^{-3}). This can be compensated to a certain extent by a more powerful system.

4 Wearable stimulator design

In this system there are in theory two ways of transmitting information though a magnetic field to an SMI. In a first case, the field is fixed and independent from the user. For three-dimensional information, its shape is manipulated to reflect the information. For example a magnetic field in the form of a virtual object is projected into space and the user is free to touch it. For non-three-dimensional information, it suffices to make the field uniform and to vary the signal according to the information. For example for Morse code the signal varies between two frequencies and can be felt uniformly throughout the space. The works of Q. Zhang, H. Dong and A. El Saddik [**?**] come close to this technique. In their version a virtual display is created by an array of electromagnets and can be explored using a glove with magnets on it. However, this example is based on a continuous field and the repellent effect thereof on the glove. A comparable version for SMIs would rely on alternating fields and the ability of SMIs to detect them even at low intensity. While this option is ideal for large-scale 3D display applications, it inherits all of the issues associated with the formation of large and complex shaped magnetic fields.

In this second case, the field is fixed relative to the implant. In the case of our finger SMIs it can be produced by a ring or a bracelet for example. This time, to produce three-dimensional information, the position of the fingers in space will have to be monitored in real time in order to determine the appropriate stimuli in relation to their movement and position. This method has the disadvantage of having to equip the user with a device. However, the shape of the field does not matter as long as it encompasses the implant and there is full control over each individual implant's stimulation at all times. In addition, the magnetic field to be produced is of much smaller scale, which makes the hardware much easier to design.

We therefore opted for the second option for the control it offers and the simplicity of its design. However, our conclusions should generally apply in both cases.

Initially we used a simple copper coil as used in [**?**] but after testing other alternatives we found that an unshielded axial inductor of just 7 mm provided a comparable field and vastly simplified the fabrication. The support was 3D printed in PLA and thin enameled copper wires connect the ring to the amplifier.

Given the desired frequency and intensity range we have decided to treat our signals as standard audio. The disadvantage of this method is that the production of frequencies below 50Hz is often limited by the hardware. However, it offers the advantage of making use of the protocols and audio channels of any common device (bluetooth, aux outputs, etc.). The rings are therefore connected to the outputs of a portable audio amplifier. This design can be made portable and compact using a 5 W, battery powered amplifier, and we can take advantage of a stereo amplifier to stimulate two fingers independently. The amplifier can be small enough to be worn on a bracelet.

InductorRingCoin.png

Fig. 6. A ring design utilizing a single axial inductor on a 3D printed base.

The inductor is chosen such that its resistance limits the maximum current that can be produced by the amplifier so that it corresponds to the maximum current supported by the inductor. In this way no additional components are needed and the inductor is used to its full potential. This system meets our main criteria:

- At least two fingers can be stimulated independently.
- The fabrication is easy and the performance of each ring is consistent.
- The device is discreet and is not restraining the user.

5 Haptic rendering of a virtual environment

Based on the limitations and advantages of this method here is an overview of potential use-cases at the moment divided into three categories We propose to use SMIs as a haptic feedback device in virtual environments, augmented reality and robot control. They would provide pressure and texture feedback while retaining an extremely low mechanical complexity and low constraint for the user. We will be using Unity to construct a VR scene and a LeapMotion to keep track of the user's hands within this scene. The previously designed device will produce a feedback corresponding to the hand's (more specifically the fingertip) overlap and movement relative virtual objects. From the 3D virtual interaction we first extract the depth of penetration of the fingertip in the object perpendicularly to the closest object surface point. This value will directly correlate to the felt pressure. The pressure will be defining the amplitude of the feedback signal. In this simple scenario the signal is sine-wave of low frequency (around 50 Hz)for a finer amplitude discrimination [?]. Every material has a default ”surface thickness” that defines the depth at which maximum amplitude is reached. This simulates the softness of the fingertip. An additional value can be added to represent the object’s softness.

Then we try simulating texture. For that we assign each material a spatial period representing the coarseness of it’s texture. We then calculate the tangential velocity of the fingertip to the object’s surface and with the following formula [?] we deduce the feedback frequency: $F = tangentialvelocity/spatialperiod$ This frequency can the be applied as an amplitude modulation on our previously described signal or can directly replace the 50Hz base frequency. Sadly the calculation of the tracked finger’s velocity introduces a lot of unwanted noise as opposed to the simple collision tracking used for the pressure simulation. This is of course due to the tracking precision of the LeapMotion controller but also to the natural shaking of a hand in empty space (the shaking would not be present when touching an actual physical object due to friction). In the optimal lighting condition for the hand tracking and by filtering the values with a rolling average we still get spikes in absolute velocity of up to 6 mm/s. This can be reduced by further filtering but then the input delay becomes noticeable. This means we can either threshold the texture simulation to a minimum velocity which gives inconsistent feedback on slow movements or the feedback can be left as is but the feedback for a static touch will remain noisy. We found the second option much more distracting.

Add section on characteristic feedback here (buttons and other recognizable punctual feedbacks)

6 Haptic rendering of alternative sources

When considered as less disrupting alternative to visual (screens) or audio(speakers) input SMIs can be envisioned as a new discrete information streaming route from digital devices to the brain. In this first idea the device could be connected to sensors of any type effectively creating what is referred as sensory substitution. A common example is using an ultrasound range finder to aid in the navigation of blind people. In this example a feedback is given relative to the distance of the person to an obstacle. In a similar way a microphone can be used for the deaf. This last example has been tested extensively using surface of the skin vibration with very conclusive results. With training participants were capable to recognize and differentiate sounds in [?]. This is good evidence that similar results if not better could be achieved with SMIs. The interesting lead on this option is to think of all the possible ”artificial senses” one could learn. The ”North Sense” trans-dermal implant is also a great example of what can be done through sensory substitution. Created and used by Liviu Babitz, it constantly notifies the user of their orientation through a vibration on the chest. Over time users have reported being intuitively aware of their geographical orientation without consciously paying attention to the implant.

7 Experiments

7.1 Haptic rendering

7.1.1 Material and methods

The experiments on haptic rendering will be done using Unity combined with a Leapmotion controller placed flat on the desk in front of the user. For the stimulation the device detailed earlier will be used.

The first experiment will aim at determining the extent of virtual 3D shape recognition using only the haptic feedback of SMIs. To do so the test subject will be equipped with our device. Ideally two rings will be used on two implants unless the subject only has one in which case only one will be used. The subject will be seated at an empty desk with just the Leapmotion controller in front of them. They will be told that there is a shape in front of them at eye level and will be given time to touch the shape until they are ready to make a guess as to what shape is presented. No visual feedback will be given. The feedback provided during the experiment will be the pressure feedback with no texture of a randomly selected shape. The shape will have overall dimensions under 30 cm in the real world so as to fit within the Leapmotion’s field of view and be easily within reach of the subject. We can use simple solids that are easy to describe: cube, sphere, pyramid, cylinder.

In a second experiment we use a similar setup. In the space in front of the subject will be a virtual path formed of straight segments going from the left to the right with a random amount of corners (0 to 5). The subject is asked to follow the line from the left to the right while counting the number of corners. This can be repeated while reducing the angle of the bends which should make the counting harder or the thickness of the path to make the following harder. We will be monitoring the answers as well as the followed trajectory.

In this last experiment we wish to prove the subject’s ability to discriminate between the force feedback of multiple different virtual buttons. The subject will be seated in front of a screen and the Leapmotion controller. On the screen will be represented the virtual environment consisting of an array of five large buttons on a wall facing the user and a representation of the user’s hand in that space. The buttons are animated and can be ”pressed” by the user. A randomized ”hardness” will be attributed to each button. The subject will then be asked to press the buttons and rank them in order of felt hardness using the stimulation device.

It would be interesting to test the lowest detectable amplitude of a 200Hz sine so that we can compare the results with [?] I. Harrison’s and therefore know if changes in design of the implant in the last years make a significant difference in sensitivity. To do so we would use a fixed coil of similar dimensions as in [?] Harrison’s paper. On the bottom center of the coil we place a gaussmeter probe and we also monitor the drawn current. The subject then places their finger in the center of the coil and either no signal or a signal of randomized amplitude is sent through the coil. Each time the subject says if the stimuli was felt. We expect lowest thresholds around 0.005 mT instead of the 0.03 mT average found previously. Also the gaussmeter will allow us to validate the estimated field strength as we expect that there is a significant difference between estimated and measured values.

Additionally the previous experiment could be repeated with varying frequencies for a sine, square and sawtooth wave to obtain sensitivity curves for each 3 in a more reliable way. This might take some time though as there is 42 frequency-signal type configurations to be tested.

Finally we could validate my categorization of sensations 3.4 by giving a series of stimuli to the subject and asking them to assign a category to each. If the results match between subjects then the description can be considered as accurate.

7.1.2 Results

7.1.3 Discussion

7.2 Haptic rendering of alternative sources

For this second set of experiments we wish to test the understanding of basic information when transmitted through SMIs.

7.2.1 Material and methods

Firstly we would like to experiment with the transfer of continuous information such as provided by most environmental sensors. We will use the on-board compass of the android device to keep the subject aware of their current cardinal orientation. We hope that the subject will be capable of keeping track of their orientation independently of visual cues and memory. To test this the subject will be equipped with the android device in a frontal or rear pocket making sure that it will be held firmly against the body and not rotate relative to the body. They will then be equipped with the stimulating device and blindfolded. The subject is told to memorize their orientation. We finally proceed to spin the subject around and ask them to face back to their original orientation. This will be repeated five times without any stimuli and five times with it.

7.2.2 Results

7.2.3 Discussion

7.3 Further research

7.3.1 Long term sensory substitution

We're interested in exploring the extents of sensory substitution through this new medium. An idea would be to use audio signal of sound or speech to the stimulate the implants. To get the best results the signal would have to be remapped in the frequency domain from it's original range to something close to our tactile sensitivity. Of course remapping the full audible spectrum (20-20,000Hz) to our limited sensitivity of 10-300Hz would lead to an extreme loss of resolution but simple sounds such as speech use a much more reasonable range. Hopefully, through extensive training, simple sounds or speech could be understood. Alternatively method's like the ones used in the Neosensory Buzz [**?**] might be applied. If it ever turns out that such complex information can be interpreted through this medium it's design simplicity and convenience will shine in many fields like helping with disabilities, discreet communication, information streaming in high stress scenarios [**?**] and of course augmented reality.

7.3.2 Shaping the magnetic field

An other lead that we hinted at earlier is the use of this technology on much larger scales. Assuming it is possible to produce fully controllable room-sized magnetic fields then a user within that space could be provided with information while being completely free of any equipment. This could in theory be used to render full scale tactile virtual environments, establish silent and targeted communication or even 3D guidance. An obvious use for that would be in VR entertainment but it could also be used in dangerous or high stress workplaces. Of course the use of SMIs in such a large scale depends largely on our ability to produce and manipulate magnetic fields which is an ongoing filed of research to this day.

8 Conclusion and Future Work

The conclusion goes here.

Acknowledgments

The authors would like to thank...

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Axel Fougues Biography text here.

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Abderrahmane Kheddar Biography text here.