# Haptic Implants

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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 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*—Subcutaneous magnets, implant haptics, wearable haptics.**

## I. INTRODUCTION

HAPTIC implants could term any technology that enables providing or enhancing human haptics by implanting an artificial component of technology in a living organism. This type of haptic technology is not thoroughly 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.). Current existing haptic technologies are external devices that convey haptic information 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 [1].

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 haptics (that we could also term *cyberhaptics* or *cyborg haptics* or *haptic bionics*) can offer tremendous perspectives and challenging investigations for new knowledge and applications. We are all cyborgs already as we relay and depends on several devices (and even chemicals) 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 sub-dermal magnetic implants or SMIs in short, Section II). Magnetic implants appeared in the early 2010's among the biohacking community and have since vastly evolved both in design and uses. They consist of a strong magnet encapsulated in a biocompatible material and are usually implanted right beneath the skin in the hypo-dermis. These have found many uses over the years as practical tools, entertainment or wireless earphones. The ones we focus on are particularly small and placed in the fingertips to give the user a sense of magnetic fields: when the implant interacts with an external field, it moves or vibrates among the user's nerve endings. This simple system provides the ability to detect, touch and identify fields with surprising precision as studied in depth in [2].

We aim at showing the feasibility of using implantable magnets as haptic rendering device in some use cases, like feedback for virtual and augmented reality. Magnetic implants would provide a mechanically simpler and potentially scaleable approach to haptic rendering. Most importantly they introduce the possibility of haptics through sub-dermal, permanent technologies.

## II. BACKGROUND

### A. Sub-dermal implants and cutaneous mechanoreceptors

Among the skin's mechanoreceptors, i.e., the nerve endings dedicated to tactile stimuli, it is the quickly adapting (QA) that are mostly involved in the perception of the implant, see [3]. They are composed of Pacinian and Meissner corpuscles that are receptively sensitive to the frequency ranges 200–300 Hz and around 50 Hz which loosely corresponds to the detectable frequency range of the implants [3].

Since they interact with the mechanoreceptors directly or within internal soft tissue rather than through the epidermis, it is fair to expect a different response to an identical stimuli. Indeed when I. Harrison [2] compares superficial and implanted magnet performances there are some differences in particular in amplitude discrimination where implants showed a significantly higher sensitivity. This difference might be explained by the superficial magnet's movement being constrained by the the outer skin layers while the entirety of the implant's energy is transferred directly to the underlying layers.

Additionally we must take into account the evolution of magnetic implants as they seem to have changed a lot during the last decade. Firstly the highest achievable grades (strength) of the magnets used have increased and will probably keep increasing. An approximative 20% increase in field strength between the implants used in 2018 [2] and the ones we use here. The coatings used have also changed to be thinner further reducing the excess mass of the implant. Both these factors

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impact the sensitivity of the implant as they increase the effect that an exterior field can have upon it by reducing its size and mass while increasing its intrinsic field.

### *B. Haptic feedback and artificial tactile stimuli*

When it comes to producing a tactile feedback many techniques have been proposed and used as seen in [4]. Nevertheless there are two main limitations 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 haptic display devices usually involve more or less complex mechanical systems (with the exception of electro-tactile stimulation [5]). 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 [6] solves these issues and makes it possible to produce the sensation of 3D shapes in empty space [7]. We can also mention the air-jet technique although it's much less versatile compared to ultrasound [8]. Still, the ultrasound technique has its own limitations:

- The stimulation range is limited to tens of centimeters [9].
- 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 [9] 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.

With implantable technology we hope to mitigate a majority of those issues, yet at the cost of being invasive.

## III. IMPLANTS FOR HAPTIC RENDERING

### *A. Sub-dermal magnetic implants, SMIs*

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. We propose integrating technology directly to the body. This might sound dangerous and intrusive but as we see in Sec. III-A2 it can be extremely simple both from an engineering and a medical point-of-views.

Implants are not a novel concept and have been used extensively for decades in the medical field. More recently [10] proposed using a magnetic implant after their previous work using magnets on fingernails in [11]. The implanted magnet provides novel forms of input (by measuring the relative position between the magnet and an on-body device) and output (an electromagnetic fields can actuate the magnet to provide output by means of in-vivo haptic feedback). There results suggests that *in-vivo* vibrations are mediated by different receptors than external vibration. Tracking the magnet and actuating it provides opportunities for encoding information as material experiences. Another recent example uses implanted magnets to monitor joint motions and named the technology: magnetomicrometry [12]. 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.

*1) Implant design:* The implant being placed under the skin it must obviously be small in size and volume. 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 ($3 \times 1$ mm disc) has become a standard because it is affordable 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 (and more recently N55). We can see that in earlier studies [3] N48 was used and therefore we can expect significant differences in sensitivity.

Neodymium (like most materials) is unfortunately not biocompatible and requires a coating. This is the main problem in the design of SMIs, because the non-magnetic mass / 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 ensuring a long life in the face of wear. With current manufacturing constraints, the possible options are as follows: silicone, titanium nitride, glass, parylene and more recently titanium. Each with inherent advantages and disadvantages.

*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 [3]. 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 between 3 and up 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.

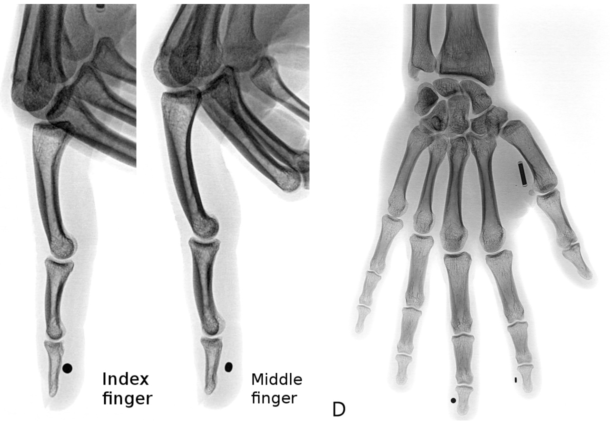

Fig. 1. X-Ray showing the two identical finger SMIs and a larger glass-encased magnet between the thumb and the index.

*3) Use-case example:* First author's two finger implants were made prior to this research (25/09/2019) for personal augmentation. As expected they provide the ability to sense magnetic fields at close proximity. For the locations, the right side of the tip on the right middle and index fingers, see Fig. 1. These fingers were chosen for being the most intuitive way to feel something. They are both on the right sides so that they would not stick to each other, which could become annoying.

As visible in the full hand X-Ray, see Fig. 1, the two small disks have settled in a different orientation. Although they are free to rotate under a strong force it seems that they still default to this position three years later. This can be explained by the process of encapsulation, where the surrounding tissue grows back to form a capsule around the implant, see [12]. This capsule having taken a specific shape can deform but will usually push the implant back to a default position. Although this almost 90 deg offset in orientation has produced a slight difference in sensitivity of magnetic fields depending on their orientation, the contrast is barely noticeable.

A larger magnetic implant is present in the soft tissue between the thumb and the index, see also Fig. 1. This implant, commonly referred to as xG3, is a $15 \times 3$ mm Neodymium rod axially magnetized within a glass capsule. Due to its increased mass and friction it requires much stronger fields to be moved and the location is not ideal for sensing. So we won't be focusing on this one even though it might be stimulated too as a byproduct, and left to future research as its shape and mass should respond better to lower frequencies.

## B. 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 haptic display:

- 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 signal mapping. The information can be spatial because the magnetic field is continuous in space and the user can touch it and explore its shape.

There are in theory two ways of transmitting information by a magnetic field to an SMI:

In the first case, the field is fixed. 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 work in [13] is close to this technique. In their version a virtual surface 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 of 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 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 will have to be monitored in real time in order to determine the appropriate stimuli in relation to their movement in space. This method has the disadvantage of having to equip oneself with a device. However, the shape of the field does not matter as long as it encompasses the implant and there can be full control of each individual implant at all times. In addition, the magnetic field to be produced is of much smaller scale, which makes the material much easier to design. In a way this is similar to the uniform fixed field but with the advantage of individual control of the implants.

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

## C. Sensitivity and sensations

We also tested the sensitivity at different frequencies and signal types, see Fig. 2 in order to determine more precisely the usable frequency range. This will allow us later to adjust the feedback intensity regardless of the signal.

Our results show that the SMI is sensitive to alternating magnetic fields close to microTesla (the earth magnetic field is around 0.03–0.06 milliTesla and a fridge magnet 5 milliTesla, however these are DC fields). This is much better than the sensitivity of a magnet on the skin surface. The frequency range of 50 to 300 Hz seems to be the most suitable, although the type of signal influences the range. For example, signals

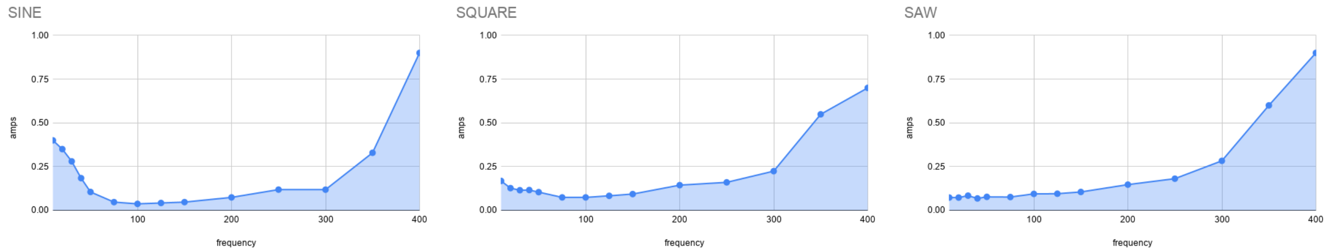

Fig. 2. Sensitivity in the frequency range 10–400 Hz to a sinusoidal (left), square (middle), and sawtooth (right) stimuli signals.

with abrupt changes in polarity such as the sawtooth signal are more effective at very low frequencies ($< 50$ Hz).

Finally these tests varying both signal intensity and frequency allowed us to "map" the different perceived feelings for a given signal. Although based on the subjective feeling of a single person this description attempts to establish the basic terms and definitions that can be refined and adjusted later when tests on a more significant sample are possible. The range of sensations that can be experienced can be categorized as follows:

- *Incoherent* (I): noisy, random or unpredictable feeling.
- *Continuous* (C): feels a sliding finger over fine fabric or soft fur. Doesn't feel like a vibration but like a light touch.
- *Vibration* (V): feels as a soft vibration whose frequency is clearly discernible. The sensation is not very localized and dissipates through the finger. Comparable to a coarse cloth.
- *Buzz* (B): feels like a strong vibration that reverberates in the bone. Tension on the implant area can be felt at the same time. Gives the sensation of a vibrator or sliding your finger along a wire mesh.
- *Tapping* (T): feels as a localized tapping or tapping sensation over the implant area at a speed equivalent to the frequency used.
- *Deformation* (D): a sensation of localized skin deformation, such as rolling a small ball between the finger and a surface.
- *Pull* (P): very localized sensation of pulling or pressing in one direction (the direction may be difficult to determine). Similar to T but continuous. The sensation fades quickly due to the adaptation of the mechanoreceptors to the stimulus (a strong magnetic field or constant hand movement is required for a sustained sensation).

The order of the feelings corresponds somehow to the frequencies producing them; high frequencies leaning towards I and low frequencies leaning towards D but the type of signal strongly influences the type of feeling and its frequency distribution. For example, a sawtooth signal will produce a very distinct T while a sinusoid will tend much more towards a D. Hence, depending on the signal, each of these feelings can appear more "muffled" or more "sharp" although grouped in the same category. The evolution of the sensation as a function of a signal parameter is continuous, so the limits of the denominations given are not strict.

## IV. WEARABLE STIMULATOR DESIGN

In order to experiment our ideas, we devised a device that transforms haptic signals into a magnetic field. For this we have considered many options, including a device in the form of a bracelet. This bracelet could consist of a single large electromagnet encompassing all the implants of the hand in a single field or of a set of electromagnets arranged in a circle. This second option would theoretically have allowed the creation of complex shaped fields, essentially forming a "magnetic display", as in [13], around the hand.

Fig. 3. Ring worn at close proximity to the implant.

The alternative is rings whose body constitutes the electromagnet. In order to test all these different configurations and the ways to optimize the magnetic flux, we used a finite element analysis software (Finite Element Method Magnetics) simulation. Unfortunately, obtaining the sufficient field range for this application would have required the manufacture of complex custom-made coils with metal cores and the final format did not necessarily meet our criteria. Finally we have chosen a new system in the form of rings using an unshielded axial inductor to produce the signal. The support rings are modeled and printed in PLA, see Fig. 3 (rings in green).

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 50 Hz is often limited by the hardware. However, it offers the advantage of being able to use the existing protocols and audio channels of our devices (bluetooth, aux outputs, etc.).

The rings are therefore connected to the outputs of a portable audio amplifier. Initially we considered the use of custom rolled coils however the use of inductors proved to be more compact and more coherent while the loss in performance is negligible. Due to their small size and the nature of the inductor used, bands must be worn at implant level, as illustrated in Fig. 3.

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. We can of course use the two stereo channels to control two rings separately. For our rings, a 5 W two-channel amplifier proved to be sufficient. Therefore the amplifier is only a few centimeters. We use power cable and audio-jack cable for signal input. The rings are connected to the outputs of the amplifier by very fine wires of about 1 m. 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 not cumbersome and is not restraining the user and fingers motions.

A wireless version with a Bluetooth amplifier and a small on-board battery is also made, Fig. 3 but the delay introduced by the Bluetooth protocol was often important. A held version with a finished design in a solid PLA enclosure was made in parallel, see Fig. 4. Although not usable for AR and VR it was very convenient for testing and can be used in many other use-cases some of which are mentioned in the concluding section.

Fig. 4. Ring worn at close proximity to the implant.

## V. HAPTIC RENDERING OF A VIRTUAL ENVIRONMENT

SMIs can be used as haptic feedback device in virtual environments, augmented reality and robot control. We focused on investigating SMIs in producing haptic feedback in a virtual environment, Fig. 5. For example when the user touches a solid virtual object s/he should feel contact forces as feedback. We are also interested in characteristic sensations such as the click of a button and in simulating the feeling of textures on virtual surfaces.

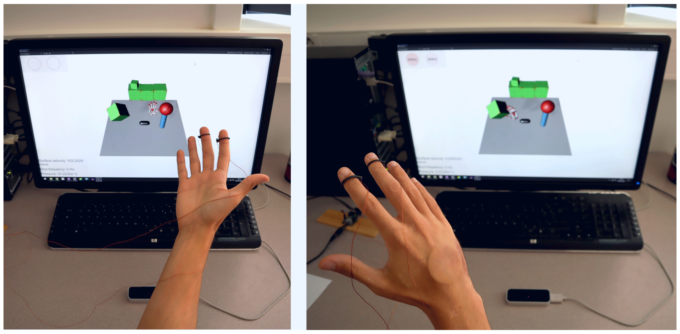

Fig. 5. Ring worn at close proximity to the implant.

We use Unity to construct a virtual scene and a LeapMotion to keep track of the user's hands within this scene, Fig. 5. Haptic features induced by the interaction of the hand with the VR objects are mapped into suitable signals and subsequent magnetic field, see Fig. 6. We take advantage of Unity's existing audio pipeline to produce various types of signals with configurable amplitude, frequency and modulations. When a stimulus is launched, a coroutine is created. It will be in charge of updating the audio filters in real time according to the information extracted from the scene (or from another information stream depending on the stimuli type).

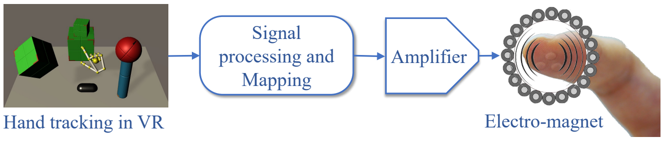

Fig. 6. Experimental setup used to experiment VR haptic feedback using Unity and a leap-motion for hand tracking.

### A. *Pressure/collision feedback*

Since the operator's hand is not constrained in VR, one shall give the illusion of resistance or at least effectively inform the person of the properties of the contact with the object when it occurs. In order to produce the sensation of pressure we vary the amplitude of the signal (besides, the type of the signal is not important). However we provide a C-type feeling (which is equivalent to high frequencies) although the amplitude discrimination seems to be better for low frequencies [2]. We took a compromise with a 100 Hz sinusoid stimuli.

The pressure exerted is proportional to the penetration depth (known from collision detection). Over a predefined margin of a few millimeters of depth the amplitude varies from 0 to its maximum. In ordre to feedback also different stiffnesses, a hardness parameter is assigned to the objects. An additional depth margin inversely proportional to the hardness will be added. Therefore the maximum pressure for a soft object will be reached deeper. This relatively simple rendering mapping has proven to be sufficient to recognize simple shapes (spheres, cubes) by touch and without visual indication.

### *B. Texture rendering*

To produce a surface feel, we assign to each material a spatial period representing the roughness of its texture. We then compute the tangential velocity of the fingertip on the object surface, in other words, the speed at which the finger slides on the surface. We deduce the frequency produced by this interaction [14]: $f = v_t/p_s$; with $f$ the frequency produced, $v_t$ the relative tangential velocity of the finger in contact with the surface and $p_s$ the spatial period of the texture. This frequency can be applied as an amplitude modulation on our previously described signal, or can directly replace the base frequency. Unfortunately, finger tracking introduces a lot of unwanted noise into the velocity calculation. This is due to the tracking accuracy of the LeapMotion controller, but also due to the natural tremor of a hand in empty space (the tremor would not be present when touching a real physical object due to friction). We synthesized a filter that attenuates these noises. Despite the persistent noises the rendering is quite interesting and it is possible to dissociate different textures. With a more powerful tracking and/or a more advanced filtering the rendering could be further improved. However the combination of force feedback and texture feedback as well as the lack of friction will remain problematic.

### *C. Other possible renderings*

We considered feeding back the “click” of a button or a switch. We chose this example because it is intuitive and its feel can vary from one button to another. After challenging producing the stimulus based on non-smooth mechanics, we realized that in most cases the audio produced by the button is very similar to the physical feel of it. Therefore, we directly used audio recordings as stimuli. It resulted is a sensation very close to the real experience.

SMIs can be envisioned as a discrete information streaming route from digital devices to the brain. 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 [15]. 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.

## VI. CONCLUSION

We present a new category of haptics displays that can be implanted, we named haptic implants. This preliminary study, although subjective, opens wide doors for challenging perspectives in the haptics domain. A strong limitation of haptic implants is that they are invasive. As a consequence, it is hard to establish studies on a large number of subjects, as in most of the cases the implants and their disposition are different. We think that we have covered a tiny number of applications, there are plenty of usages that are possible in VR, AR and robotics. More importantly however, haptic implants can reveal great potentials in amputees to restore haptic feedback from prostheses tactile sensors [16].

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