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Interaction with Implanted Devices through Implanted User Interfaces[1)]

Christian Holz, Tovi Grossman, George Fitzmaurice, and Anne Agur

In his seminal article, Mark Weiser wrote, ''the most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it'' [1]. Weiser's seminal vision is close to becoming today's reality. We now use mobile devices to place calls and send emails on the go, maintain our calendars and setup reminders, and quickly access information – anywhere, anytime. While these devices have not yet disappeared, the transition to ultra-small mobile devices is undeniable [2], and mobile devices have become an integral part of our lives.

In the medical domain, some devices have indeed reached the state of virtual invisibility. People have started to receive *implanted devices* for medical purposes, such as pacemakers and hearing aids. Active medical implants typically maintain life-crucial functionality (e.g., pacemakers), improve body functionality to restore normal living (e.g., hearing aids), or monitor the user's health [3]. Passive implants are also commonly used for medical purposes, such as for artificial joints. Active implanted devices provide a large number of benefits – benefits that are fundamental from a medical point of view and at the same time benefits the mobile community is striving toward: implanted devices along with the information they store always travel with the user; users can never lose or forget them, nor is there a need for manually attaching them. Implanted devices are available to the user *at all times*. Although they are invisible to other people, over 3 million people have implanted pacemakers alone [4].

However, current implanted devices involve a number of downsides. Although they are part of the user, users have currently no way to interact with them. To check on the status of their pacemaker, for example, a user needs to see a physician. If a pacemaker is running low on battery, the user will need to undergo replacement surgery, along with the risks and costs that such an operation entails.

[1)]The material presented in this chapter is based on the following publication: Christian Holz, Tovi Grossman, George Fitzmaurice, and Anne Agur. 2012. Implanted user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '12). ACM, New York, NY, USA, pages 503–512.

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Since it is unclear how a user might interact with an implanted device directly, we investigated the *implanted user interfaces* that such small devices provide when implanted underneath humans [5]. Although implanted devices have existed for a long time in the medical domain, they currently support only limited interaction and cannot support personal tasks. Unlike other types of mobile devices, such as wearables [6] or interactive clothing [7], implanted devices are with the user *at all times*. Implanting thus truly allows always-available interaction [8]. Before implanted user interfaces can become a reality for *interactive tasks*, numerous questions must be considered.

We discuss four core challenges of implanted user interfaces: how to sense input through the skin, how to produce output, how to communicate among one another and with external infrastructure, and how to remain powered. In the rest of this chapter, we first discuss these four challenges and then perform a technical evaluation, where we surgically implant seven devices into a specimen arm. We evaluate and quantify the extent to which traditional interface components, such as LEDs, speakers, and input controls work through skin (Figure 8.1b,c). Our main finding is that traditional interface components do work when implanted underneath human skin, which provides an initial validation of the feasibility of implanted user interfaces.

Motivated by these results, we demonstrate how to deploy a prototype implant on participants. We report the results of a qualitative evaluation using the prototype device (Figure 8.2a), in which we collected user feedback. As a substitute for actually implanting this device, we place it under a layer of artificial skin made from silicon, which affixes on the user's skin (Figure 8.2b). We conclude our exploration of implanted user interfaces with a comprehensive discussion of medical assessment, limitations, and projection into the future.

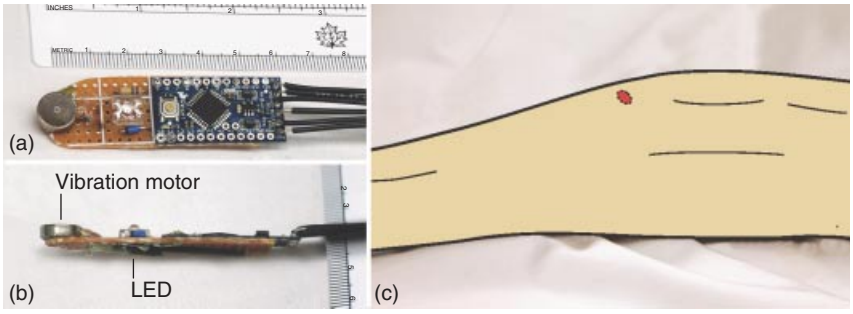

Figure 8.1 *Implanted user interfaces* allow users to interact with small devices through human skin. (a,b) This output device is implanted (c) underneath the skin of a specimen arm. The output is shown in Figure 8.16a. *Note: Throughout this chapter, illustrations have been used in place of actual photographs of the specimen to ensure ethical and professional standards are maintained.*(Adapted from [26] with permission.)

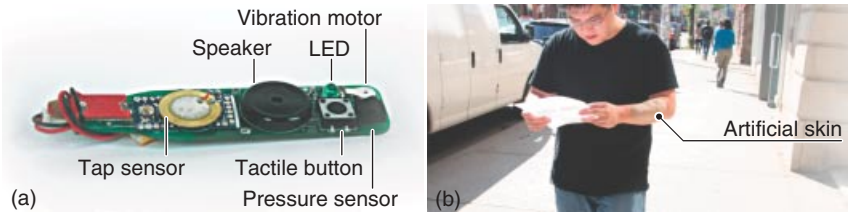

Figure 8.2 We covered a prototype device (a) with a layer of artificial skin (b) to collect qualitative feedback from use in an outdoor scenario. Participants received output triggers *through* the artificial skin and responded with input. (Adapted from [26] with permission.)

8.1 Implanted User Interfaces

We consider *implanted devices* as devices that are surgically and permanently inserted under the human skin. Implanting devices that possess user interfaces would allow users to *directly* interact with them, allowing them to support a wide range of applications and tasks, beyond the medical usages prevalent today.

Implanted devices have several advantages over mobile and wearable devices. First, implanted devices do not need to be manually attached to the user's body. They stay out of the way of everyday or recreational activities (e.g., swimming or showering). Second, implanted devices have the potential to be completely *invisible*. This would avoid any social stigma of having such devices. Third, implanted devices, along with the information they store and provide, always travel with the user; the user can never lose or forget to take them. The devices and applications become *part* of the user.

Humans have experimented with adding new abilities to their bodies, such as implanting a small magnet to their finger [9] or an RFID chip into their body. Masters and Michael discuss issues surrounding human-centric applications of RFID implants, such as automatically opening doors and turning on lights [10]. Warwick's Project Cyborg investigates user interaction through an implanted RFID chip with devices in the proximity, as well as the interaction of implants with user's nervous system [11]. Ullah *et al*. discuss in- and on-body wireless communication [12] in the context of *body area networks* [13]. Relevant work can also be found in the art community. For example, Stelarc attached an ear-replica to his arm, which used a miniature microphone to transmit recorded sounds wirelessly [14].

Despite these potential benefits, there has been little or no investigation of implanted user interfaces from a human–computer interaction (HCI) perspective. Given the continuous miniaturization of technology [2], we believe implanted user interfaces could become a reality in the future. Below, we outline some of the core design considerations, with the hope of bringing these issues to the attention of the HCI community.

8.1.1 Design Considerations

We see four core challenges associated with implanted user interfaces and their use through human skin: (i) providing input to and sensing input on implanted devices, (ii) perceiving output from and producing output from implanted devices, (iii) communication among implanted devices and with external devices, and (iv) power supply to implanted devices.

8.1.1.1 Input through Implanted Interfaces

Since implanted devices remain under the skin, they are not directly accessible through their interfaces. This makes providing input to them an interesting challenge.

One option is to use contact-based input through the skin, such as a button, which would additionally offer tactile and audible feedback to the user. Tap and pressure sensors allow devices to sense how strongly touches protrude the skin, whereas brightness and capacitive sensors detect a limited range of hover. Strategic placement of touch-based sensors could form an input surface on the skin that allows for tapping and dragging. Audio is an alternative implanted user interface. A microphone could capture speech input for voice activation.

Fully implanted and thus fully concealed controls require users to learn their locations, either by feeling them through skin or by indicating their location through small marks. Natural features such as moles could serve as such marks. Partial exposure, in contrast, would restore visual discoverability and allow for direct input. Exposing a small camera, for example, would allow for spatial swiping input above the sensor (e.g., optical flow of the fingerprint [2, 15]). All such input components, whether implanted or exposed, are subject to accidental activation, much like all wearable input components. Systems have addressed this, for example, by using a global on/off switch or requiring a certain device posture [16].

8.1.1.2 Output through Implanted Interfaces

Device output typically depends on the senses of sight (i.e., visual signals), hearing (i.e., audio signals), and touch (e.g., vibration and moving parts). Stimulation of other senses, such as taste and smell, is still only experimental (e.g., taste interfaces [17]).

The size constraints of small devices require sacrificing spatial resolution and leave room for only individual visual signals, such as LEDs. Furthermore, visual output may go unnoticed if the user is not looking directly at the source. Although audio output is not subject to such size constraints, its bandwidth is similar to the visual output of a single signal: varying intensities, pitches, and sound patterns [2]. Tactile output of single elements is limited to the bandwidth of pressure to the body and intensity patterns. Tactile feedback may be particularly suited toward implanted user interfaces, since it could provide output noticeable only to the host user and no one else.

8.1.1.3 Communication and Synchronization

To access and exchange data among each other or with external devices, implanted devices need to communicate.

If devices are fully implanted under the skin, communication will need to be wireless. Bluetooth is already being used to replace wired short-range point-to-point communication, such as for health applications (e.g., in body area networks [13]). Wi-Fi, as an alternative, transmits across longer distances at higher speeds, but comes at the cost of increased power usage and processing efforts. For interactive purposes, electrodes have been implanted for interactive purposes in the context of brain–computer interaction [18] and speech production [19].

Equipping implanted devices with an *exposed port* would enable tethered communication. Medical ports are already used to permit frequent injections to the circulatory system [20]. Ports and tethered connections are suitable for communication with external devices, but not between two devices implanted at different locations in a user's body. Such devices would still require wireless communication.

8.1.1.4 Power Supply through Implanted Interfaces

A substantial challenge for implanted devices is how they source energy. As power is at a premium, implanted devices should employ sleep states and become fully active only after triggering them.

A simple way to power an active implanted device is to use a replaceable battery. This is common with pacemakers, which typically need surgical battery replacement every 6–10 years. Rechargeable batteries would avoid the need for surgery and recharging could be wireless, through technology known as *inductive charging* [21]. If the implanted device is close to the skin surface, inductive charging may work through the skin [22]. Alternatively, an exposed port could provide tethered recharging to an implanted device. Finally, an implanted device could harvest energy from using the device or from body functions (e.g., heartbeats [23] or body heat [24]). We direct the reader to Starner's overview for more information [24].

8.1.2 Summary

We have described some of the key challenges and discussed possible components that could support the interface between the human and the implantable. However, there is little understanding of how well these basic interface components actually function underneath human skin.

8.2 Evaluating Basic Implanted User Interfaces

The purpose of this evaluation was to examine to what extent input, output, communication, and charging components remain useful when implanted underneath human skin. In addition, we provide a proof of concept that these

devices can in fact be implanted, both fully under the skin and with exposed parts.

We performed this evaluation in collaboration with the Department of Surgery in the Division of Anatomy at the University of Toronto, Canada. The procedure of the study underwent full ethics review prior to the evaluation and received approval from the Research Ethics Board.

8.2.1 Devices

We evaluated 7 devices featuring 12 controls in total, which were traditional input and output components as well as components for synchronization and powering common in conventional mobile devices. As shown in Figure 8.3, we tested four basic sensors for direct touch input: button, pressure sensor, and tap sensor. In addition, we tested two devices that could potentially detect hover above the skin: capacitive and brightness sensor. We also tested a microphone for auditory input. For output, we tested an LED (visual), vibration motor (tactile), and speaker (audio). For charging, we evaluated an inductive charging mat, and for communication, we tested Bluetooth data transfer. These devices do not exhaust all possible implanted interface components, but we chose them as some of the more likely components that could be used.

Cables connected each of the devices to a laptop computer to ensure reliable connectivity and communication with the devices throughout the study (Figure 8.4). The laptop logged all signals sent from the input components on the devices, including device ID, sensor ID, sensed intensity, and timestamp. The laptop also logged time-stamped output triggers, including output component ID, intensity, and frequency.

All active devices used an ATmega328 microcontroller with a 10-bit precision analog-to-digital (AD) converter. The chip forwarded all measurements to the laptop and also computed length of impact as well as average and maximum intensities. We also recorded all background intensities separately.

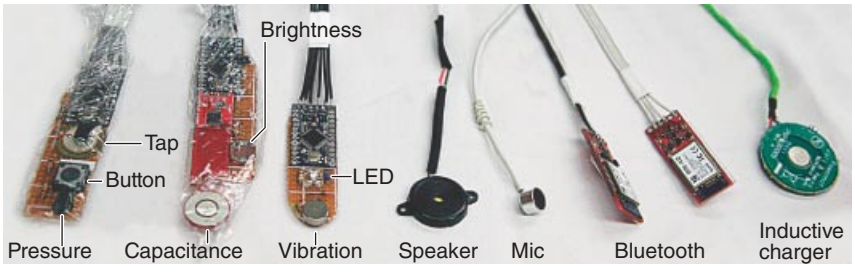

Figure 8.3 Devices implanted during the study. Plastic bags around devices prevent contact with tissue fluid. (Adapted from [26] with permission.)

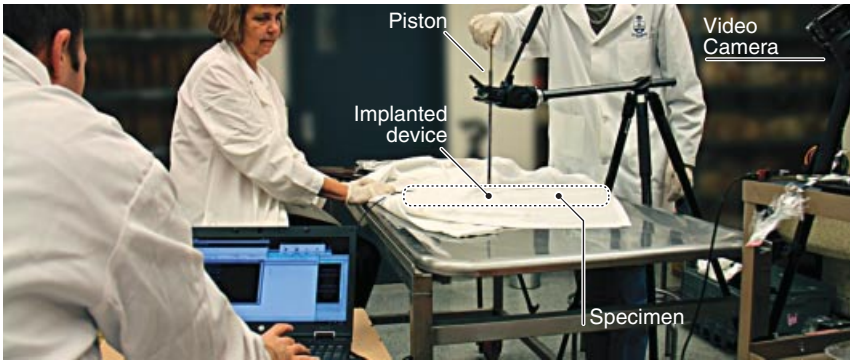

Figure 8.4 Study setup with input apparatus setup. A piston repeatedly dropped from controlled heights onto the sensors. (Adapted from [26] with permission.)

8.2.2 Experimenters

The study was administered by an experimenter and an experimenter assistant, both with HCI backgrounds, and an anatomy professor, who carried out all of the surgical procedures (Figure 8.4). Because the focus of this study was on the technical capabilities of the devices themselves, external participants were not necessary.

8.2.3 Procedure

We conducted the evaluation in two sessions. In the *baseline session*, the devices lay on the table shown in Figure 8.4. In the *implant session*, each of the seven devices was implanted into a cadaveric specimen, one at a time. An external video camera documented the entire implant session, and parts of the baseline session. The experimenter configured and initialized the devices through the laptop and monitored the incoming data, while the assistant performed the necessary interactions with the devices.

8.2.4 Medical Procedure

One lightly embalmed cadaveric upper limb specimen (dark-skinned male, 89 years old) was used for this study. With light embalming, the tissues remained pliable and soft, similar to fresh and unembalmed tissue [25]. The skin and subcutaneous tissues remained mobile.

Each of the seven devices was enclosed by two thin transparent plastic bags to prevent malfunction due to penetration by tissue fluid (as shown by the two left-most devices in Figure 8.3). To insert devices, the skin was incised and separated along

the tissue plane between the skin and underlying subcutaneous tissue at the cut end of the limb, about 7.5 cm proximal to the elbow joint, which was 20 cm from the insertion point. Once the plane was established, a long metal probe was used to open the plane as far distally as the proximal forearm, creating a pocket for the devices. Each of the devices was inserted, one at a time, into the tissue plane and the wires attached to the devices were used to guide the device into the pocket between the skin and subcutaneous tissue of the proximal forearm (Figure 8.5). Distal to the insertion site of the device, the skin remained intact. All devices were fully encompassed by skin, with no space between device and skin or tissue, or any opening.

8.2.5 Study Procedure and Results

We now report the study procedure along with results separately for each of the seven devices.

8.2.5.1 Touch Input Device (Pressure Sensor, Tap Sensor, Button)

To produce input at controlled intensities, we built a stress test device as shown in Figure 8.4. The assistant dropped a piston from controlled heights onto each input sensor to produce predictable input events.

For the pressure and tap sensors, the piston was dropped from six controlled heights (2–10 cm in steps of 2 cm), repeated five times each, and the intensities from the sensors were measured. For the button, the piston was dropped from seven heights (3 mm, 7 mm, 1 cm, 2–10 cm in 2 cm steps), also repeated five times each, and we recorded if the button was activated. Subjectively, the piston dropping from 10 cm roughly compared to the impact of a hard tap on a tabletop system. Dropping from 1 cm produces a noticeable but very light tap.

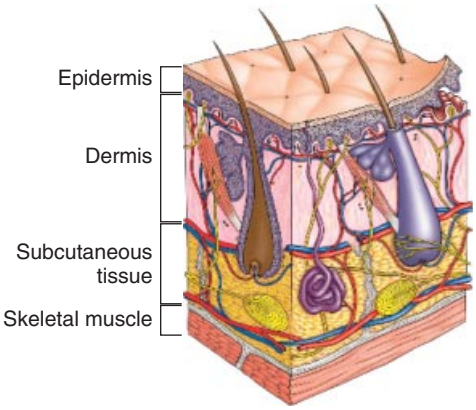

Figure 8.5 Illustration of skin layers. All devices were implanted between the skin and the subcutaneous fatty tissue. (Adapted from [26] with permission.)

Apparatus Details The pressure sensor used a voltage divider with a circular 0.2″ Interlink Electronics force sense resistor (100 g to 10 kg) and a 10 kΩ resistor. The button was a 12 mm (H4.3 mm) round PTS125 hardware button. The touch sensor was a Murata 20 mm piezoelectric disc. The microcontroller captured events at 30 kHz. The piston was a 60 g metal rod.>

Results

Force sensor: Skin softened the peak pressure of the dropping piston, whereas the softening effect shrunk with increasing impact force (Figure 8.6). We analyzed the measured voltages and, by relating them back to the force–resistance mapping in the datasheet, obtained an average of 3N in differences of sensing impact between conditions.

Button: Figure 8.7 illustrates the effect of skin dampening on the impact of the dropping piston. In the baseline condition, the piston always activated the button, whereas only dropping from a height of 1 cm and higher achieved enough force to activate the button through the skin at all times.

Tap sensor: In both conditions, the piezo tap sensor produced the maximum voltage our device could measure in response to the impact of the piston from all tested heights. The piston therefore activated the tap sensor reliably with all forces shown in Figure 8.6.

8.2.5.2 Hover Input Device (Capacitive and Brightness Sensor)

To produce hover input, the assistant used his index finger and slowly approached the sensor from above over the course of 3 s, rested his finger on it for 3 s, and then slowly moved his finger away. The assistant repeated this procedure five times for each of the two sensors.

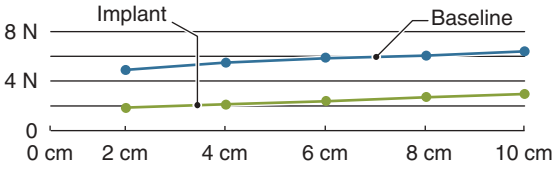

Figure 8.6 On average, skin accounts for 3 N overhead for impact forces on pressure and touch sensors. (Adapted from [26] with permission.)

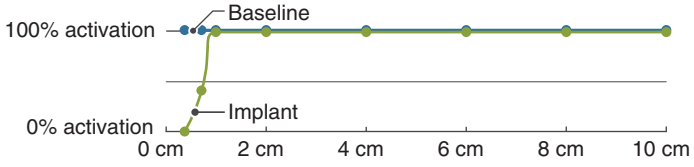

Figure 8.7 The piston activated the button from all tested heights in the baseline condition, but activated the button reliably only from a height of 1 cm and above when implanted. (Adapted from [26] with permission.)

Apparatus Details The capacitive sensor was a 24-bit, two-channel capacitance to digital converter (AD7746). The brightness sensor used a voltage divider with a 12 mm cadmium sulfide 10 MΩ photoresistor and a 10 kΩ resistor. Both sensors captured hover intensities at 250 Hz. Three rows of fluorescent overhead lighting illuminated the study room.

Results For both sensors, we averaged the five curves of measured signal intensities to account for noisy measurements.

Brightness sensor: Without the finger present, the skin diffused incoming light, and resulted in reduced brightness (Figure 8.8a). The environmental light explains the differences in slopes between baseline and implant conditions; as the finger approaches the sensor, light reflected from surfaces can still fall in at extreme angles in the baseline condition. The skin, in contrast, diffuses light and thus objects approaching the sensor result in a less pronounced response.

Capacitive sensor: Similar to the brightness sensor, the capacitive levels were offset when sensing through the skin (Figure 8.8b). The signal of a touching finger was comparably strong in the baseline condition, but caused only a milder difference in sensed capacitance through the skin.

8.2.5.3 Output Device (Red LED, Vibration Motor)

To evaluate the LED and motor, we used a descending staircase design to determine minimum perceivable intensities [27, 28]. For each trial, the experimenter triggered components to emit output at a controlled intensity level for a duration of 5 s. The assistant, a 32 year old male, served as the participant for the staircase study to determine absolute perception thresholds. The method started with full output intensity, which the participant could clearly perceive. The experimenter then decreased the intensity in discrete steps, and the participant reported if he could perceive it. If he did not, the experimenter increased output intensities in smaller steps until the participant could perceive it. We continued this procedure until

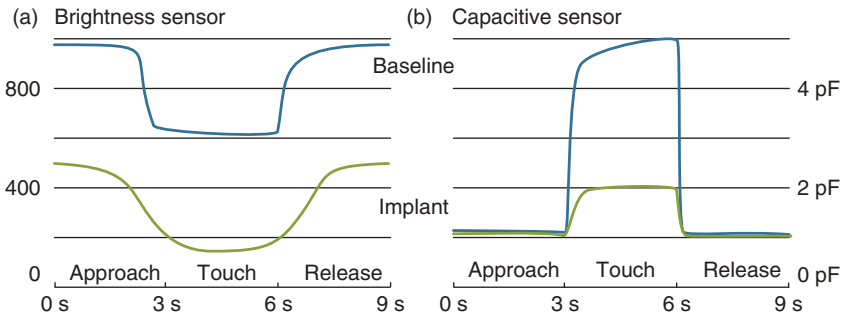

Figure 8.8 (a) Impact on sensed brightness and on sensed capacitance (b). Curves average the values of all five trials. (Adapted from [26] with permission.)

Figure 8.9 A camera captured the intensity of produced light (a) and an accelerometer measured vibration intensities (b). (Adapted from [26] with permission.)

the direction had reversed eight times [28, 29]. The last four reversal values then determined the absolute perception threshold [29].

At each step, we also measured the actual output intensities. We captured the LED output with a camera focusing onto the LED at a fixed distance, aperture, and exposure time (Figure 8.9a). An accelerometer placed directly above the vibration motor captured output intensities (Figure 8.9b).

Apparatus Details The LED was a red 3000 mcd square light. The vibration motor was a 10 mm (H3.4 mm) Precision Microdrives shaftless 310-101 vibration motor. The external camera was a Canon DSLR EOS5D and captured 16 bit RAW images.

Results

LED: The staircase methodology yielded the absolute threshold for perceiving LED output at 8.1% intensity required in the baseline condition and 48.9% intensity required through the skin. Figure 8.10a shows the actually produced intensities determined by the external camera.

Vibration motor: The accelerometer captured a signal through the skin only when the motor was powered at 40% intensity and higher; lower intensities were indistinguishable from background noise (Figure 8.10b). The baseline condition with the accelerometer resting on the motor directly shows an

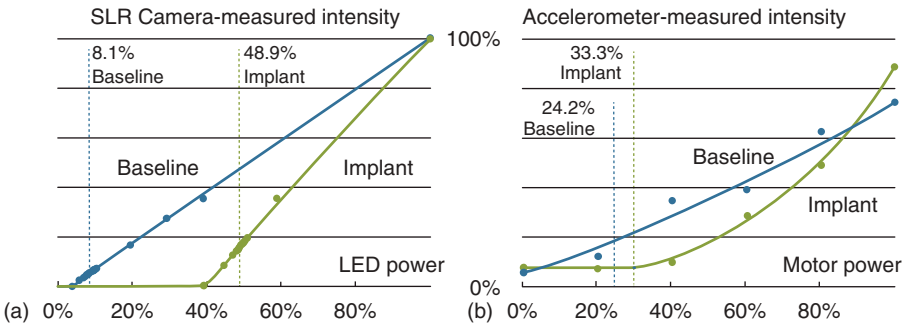

Figure 8.10 (a) Minimum perceivable LED intensity. (b) The accelerometer did not pick up a signal through skin at motor intensities of 40% and lower. Dotted lines indicate the participant's absolute perception thresholds. (Adapted from [26] with permission.)

expected linear decay. The shown values represent the mean standard deviation of the three values read by the accelerometer. The difference in personal perception of the vibration was small (24.2% vs 33.3%).

8.2.5.4 Audio Device (Speaker and Microphone)

To evaluate the speaker, we again used a descending staircase design to determine minimum perceivable audio levels. We conducted the evaluation from two distances: 25 cm (*close*) and 60 cm (*far*). These distances simulated holding the arm to one's ear to listen to a signal (*close*) and hearing the signal from a resting state with the arms beside one's body (*far*). The stimulus was a 1 kHz sine wave signal [30]. During each step, an external desktop microphone measured actual output signals from 5 cm away in the *close* condition, and 60 cm away in the *far* condition.

To evaluate the implanted microphone, we produced audio as input from two distances (25, 60 cm). Two desktop speakers pointed at the microphone and played 5 prerecorded sounds at 10 volume levels (100, 80, 60, 40, 20, 10, 8, 4, 2, 1%). Three of the sound playbacks were voice (''one,'' ''two,'' ''three,'' ''user''), one was a chime sound.

Apparatus Details The implanted microphone was a regular electret condenser microphone. The external microphone was an audio-technica AT2020 USB. The speaker was a Murata Piezo 25 mm piezoelectric buzzer. The laptop recorded from both microphones at 44.1 kHz with the microphone gain set to 1.

Results

Speaker: We first applied a bandpass filter of 100 Hz to the recorded signal around the stimuli frequency to discard background noise. The assistant could perceive the stimuli sound at a level of 5.2 dB at only 0.3% output intensity in the *baseline* session, and at 7% in the *implant* session (Figure 8.11). The perceivable decibel levels compare to other results [30]. Figure 8.11 illustrates the additional output intensity needed to achieve comparable sound pressures.

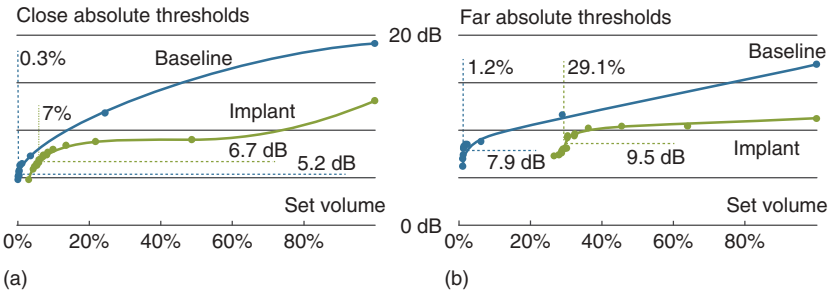

Figure 8.11 Sound perception through skin is possible, but the skin substantially takes away from the output intensity (a). This effect grows with the distance between the listener the and speaker (b). Dotted lines indicate absolute perception thresholds. (Adapted from [26] with permission.)

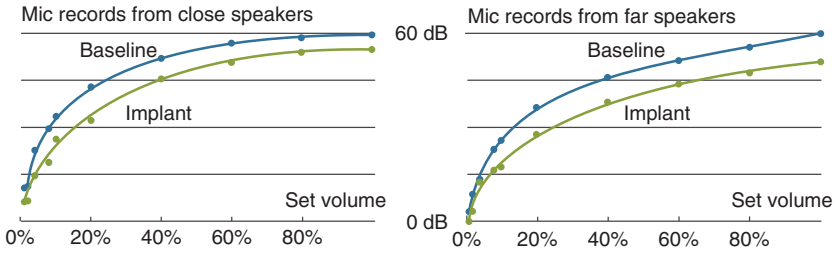

Figure 8.12 The differences in perceived sound intensities were nearly constant between the implant and the baseline session. (Adapted from [26] with permission.)

Microphone: The skin accounted for a difference in recorded sound intensities of 6.5 dB (±3 dB) for the close-speaker condition and 6.24 dB (±2.5 dB) in the far-speaker condition. At full output volume, the skin dampened the volume of the incoming sound by less than 2% when close by 25 cm away, but almost 10% with speakers 60 cm away (Figure 8.12).

8.2.5.5 Powering Device (Powermat Wireless Charger)

To evaluate the powering device, we docked the receiver to the powering mat (Figure 8.13). In the *baseline* session, the two devices docked directly. In the *implant* session, the receiver was implanted, and the powering mat was placed on the surface of the skin directly above the implant.

Once docked, we separately measured the voltages and currents the receiver supplied with a voltmeter and an ampere meter. We took five probes for each measurement, each time capturing values for 5 s for the meters to stabilize. We measured the voltages provided and the current drawn with four resistors: 2 kΩ, 1 kΩ, 100 Ω, and 56 Ω.

Apparatus Details The powering device was a PMR-PPC2 Universal Powercube Receiver with a PMM-1PA Powermat 1X. The voltmeter and ampere meter was a VC830L digital multimeter.

Results The Powermat receiver output a nominal voltage of 5.12 V in the baseline condition. Through skin, the provided voltage was unsubstantially smaller (5.11 V).

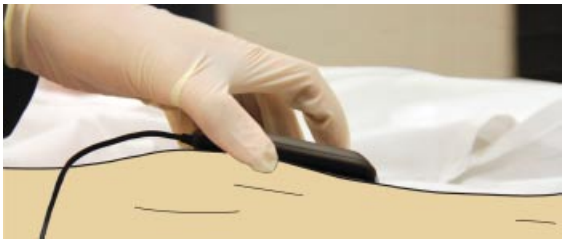

Figure 8.13 The wireless charging mat docks to the receiver, which is implanted inside the specimen. (Adapted from [26] with permission.)

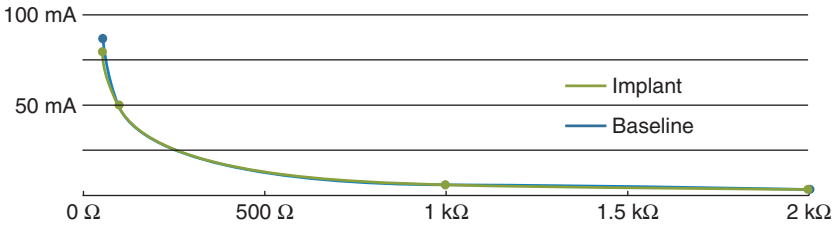

Figure 8.14 Skin affected the current provided through the wireless connection only at higher current values. (Adapted from [26] with permission.)

As shown in Figure 8.14, the skin did not impact the current drawn by the device for low resistances. For the 56 Ω resistor, the difference was 7 mA, still providing 80 mA, which should easily power an Arduino microcontroller.

8.2.5.6 Wireless Communication Device (Bluetooth Chip)

To test the performance of the wireless connection between two chips, one was external and one implanted with no space between chip and encompassing skin in the *implant* session. The *baseline* session tested both devices placed outside. We evaluated the connection at two speed levels (slow: 9600 bps, fast: 115 200 bps), sending arrays of data in bursts between the devices (16, 32, 128 kB) and calculating checksums for the sent packages. The receiving device output time-stamped logs of the number of received packages and its calculated checksum. The test was fully bidirectional, repeated five times and then averaged.

Apparatus Details The Bluetooth modules were Roving Networks RN-42 (3.3 V/26 µA sleep, 3 mA connected, 30 mA transmitting) connected to an ATmega328 controller. The RN-42 featured an on-board chip antenna with no external antenna.

Results For the slow transmission speed, no packet loss occurred in either condition. The effective speed rate was 874 B s^{-1} in both conditions (Figure 8.15a).

For the fast transmission speed, the devices received 74% of the sent packages on average in the baseline and 71% when sent through the skin (Figure 8.15b). The effective speed differed by 200 B s^{-1} (4.4 kB baseline vs 4.2 kB skin). We found no differences in direction.

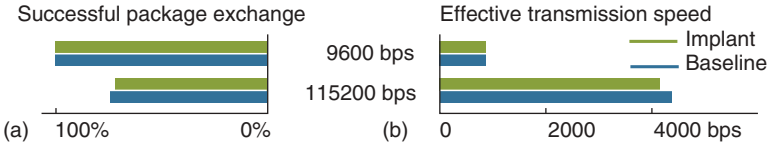

Figure 8.15 (a) Bluetooth exchanges data reliably when running slow, but comes with data loss when running fast. (b) Implanting affected fast transmission rates negatively. (Adapted from [26] with permission.)

8.2.6 Discussion

Overall, all traditional user interface components that were implanted worked under the skin, sensing input through the skin, emitting output that could be perceived through the skin, and charging and communicating wirelessly.

Regarding input, the skin required, as expected, user input to increase in intensity to activate sensor controls. Despite this required intensity overhead, all tested input sensors did perceive input through the skin, even at the lower levels of intensity we tested. This leaves enough dynamic range for the sensors' additional degrees of freedom, such as detecting varying pressure. As for hover detection, the skin incurs an offset of brightness and diminishes capacitive signals, but both sensors responded to the approaching finger.

While output appears diminished through the skin, detection is possible at low-enough intensity levels, such that output components, too, can leverage a range of intensities for producing output.

Powering the device through the skin yielded enough voltage to have powered any of the implanted devices. It is also enough to power our *3in3out* prototype device, which we describe in the next section. More measurements with lower resistances remain necessary to determine the maximum throughput of the tested inductive power supply beyond the 100 mA levels.

While skin affected the throughput of the fast wireless communication and accounted for a 3% higher loss of packages and a 0.2 kB s^{-1} drop in speed, it did not affect the slow condition. The flawless wireless communication in 9600 bps enables reliable data exchange. Results found in the related area of body area networks differ, as transmission goes through the body or arm, not just the skin [22].

8.2.7 Exploring Exposed Components

In addition to quantitatively evaluating input components, we wanted to prototype an exposed implanted interface component. To do so, we mounted a Blackberry trackball control on the back of an Arduino Pro Mini 8 MHz board and soldered batteries to it. The trackball was a fully autonomous standalone device. We programmed the trackball to emit a different light color when the user swiped the ball horizontally or vertically.

To expose the roller ball, the skin and plastic cover over the roller ball were carefully incised using a scalpel. The incision was about 3 mm in length, so that only the roller ball was exposed. Once implanted into the specimen, the experimenters took turns interacting with the device, which worked as expected. Figure 8.16 illustrates the exposed trackball. Note that this exploration took place *after* the quantitative evaluation had fully finished. The incision made for this exploration had no effect on our earlier evaluation.

Figure 8.16 (a) Actual photograph of the LED output through the skin. (b) This standalone prototype senses input from an *exposed* trackball and (c) illuminates it in response. (Adapted from [26] with permission.)

8.3 Qualitative Evaluation

To explore initial user feedback on implanted user interfaces, we built and deployed a prototype device covered with a layer of artificial skin on users. Our goal was to gain initial insights on how users may feel about walking around with an interactive implanted device and to demonstrate how such devices can be prototyped and tested outside controlled laboratory conditions.

Study Device: We built the *3in3out* device specifically for the qualitative evaluation (Figure 8.2a). It features three input controls (button, tap sensor, pressure sensor) and three output components (LED, vibration motor, piezo buzzer). A Li-Po battery powers the standalone *3in3out* device.

The device implemented a game as an abstract task that involved receiving output and responding with input. At 30–90 s intervals, a randomly chosen output component triggered the user, who had to respond using the correct input: pressure sensor for the LED, tap sensor for the motor, and button for the speaker. While the LED kept blinking, the speaker and vibration motor repeated their output trigger every 10 s. Without a response, the trigger timed out after 1 min. Participants received points on the basis of the speed and accuracy of their responses.

8.3.1 Simulating Implants: Artificial Skin

We created artificial skin to cover our prototype and simulate actual implantation with the aid of a professional prosthetics shop, which had years of experience modeling body parts. The artificial skin is diffuse and diffused light, and dampened sound and vibration in roughly the same manner as the real skin in our evaluation. Participants in the study confirmed that the artificial skin qualitatively felt similar to real skin. As the focus of this study was on obtaining qualitative feedback, we did not calibrate the characteristics of the artificial skin to match the absolute quantitative properties of skin we measured in our evaluation. We did not need

the artificial skin to match the Bluetooth properties of skin either, because our qualitative study did not include communication devices.

To create the artificial skin, we mixed Polytek Platsil-Gel 10 with Polytek Smith's Theatrical Prosthetic Deadener, which is known to produce silicone with skin-like feel and consistency. We added skin-color liquid foundation and enhanced the skin look with red, blue, and beige flocking. We then poured the silicone mixture into a mold customized to fit a human arm, added the device wrapped in Seran foil, and positioned a clay arm, so that the silicone assumed the correct shape. We then affixed the artificial skin to users' arms using ADM Tronics Pros-Aide medical grade adhesive. The final layer of artificial skin measured $4.5'' \times 2''$ (Figure 8.17) and was 1–2 mm thick above the device (i.e., similar to anterior surface skin [31], which we studied).

8.3.2 Task and Procedure

We designed a set of six primary tasks to distract from wearing the prototype device, which interrupted participants while carrying out those tasks: (i) ask a person for the time, (ii) board public transport and exit after two stops, (iii) ask a person for directions to the post office, (iv) pick up a free newspaper, (v) buy a coffee, and, finally, (vi) sit in a park, finish the coffee, and read the newspaper. Participants' secondary task was to respond to the triggers that the *3in3out* device emitted, and try to achieve a high score. The device recorded response times, errors, and point totals. The study took place in downtown Toronto, Canada, on a summer day, which represented a realistic worst-case scenario; both, direct sunlight and noise levels were very intense.

Participants first received a demonstration of the device and practiced its use. The participant then left the building to perform all primary tasks, and returned after approximately 60 min. Participants filled out a questionnaire after the study, sharing their impression when using the device in public environments and the reactions they received.

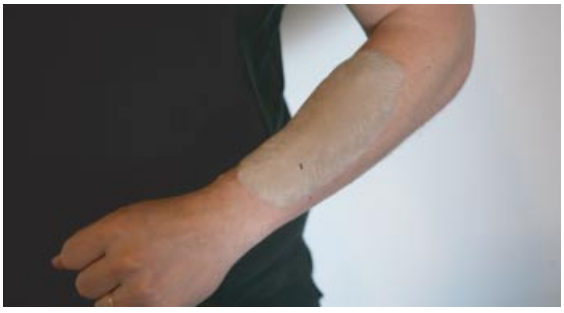

Figure 8.17 Artificial skin, created from silicon, covered the *3in3out* device to simulate implantation and allow for testing. (Adapted from [26] with permission.)

8.3.3
Participants

We recruited four participants (one female) from our institution. Participants were between 28 and 36 years old and wore the prototype device on their left arm. We reimbursed participants for using public transport and buying coffee.

8.3.4
Results

Overall, participants found the device easy to use. All liked the tap sensor (''easy to use'') and button (''easy to find,'' ''haptic feedback''), but none enjoyed the pressure sensor. For output components, all ranked the LED lowest for perception relative to the other output components, the speaker medium, and the vibration motor best (''really easy to notice''). While these results suggest that the device might work better in environments quieter and/or darker than the noisy city setting in direct sunlight, participants were able to see the LED blinking when looking at it.

While participants mentioned receiving curious looks from others when interacting with their arm, no external person approached a participant, even though they spent time in casual settings (e.g., coffee place and public transport).

Most importantly, the results of our study demonstrate that implanted user interfaces can be used to support interactive tasks. This evaluation also provides a methodology to pave the way for future evaluations and mockups of more elaborate devices and applications of implanted user interfaces.

8.4
Medical Considerations

While the goal of this paper is to consider implanted user interfaces from an HCI perspective, it is also important to discuss some of the medical considerations. Below we discuss some of the issues surrounding the feasibility of implanted user interfaces.

8.4.1
Location

In our study, the devices were implanted under the skin on the front of the forearm, just distal to the elbow joint. This location was chosen as the devices could be easily activated by an individual with the other hand and would not be in an area where damage by impact is likely. For the most part, these devices could be implanted deep into the skin in the subcutaneous tissue anywhere in the body where the devices are accessible and can transmit signals. This includes the upper and lower limbs, the chest wall, abdomen, and so on. Areas covered by thick skin, such as the palms and soles of the feet, would not be suitable for implantables, as the skin

is too thick and tough to interact. The thickness of human skin ranges between 0.5 mm on the eyelids to 4+ mm on the palms and soles of the feet [31].

The superficial placement of the devices, directly under the skin, facilitates device activation and signal transmission. The devices can be inserted between the skin and subcutaneous tissue, providing a minimally invasive approach. The deep underlying tissues, for example, muscle, would not be disrupted. Similarly, pacemakers are placed under the skin in the chest or abdominal regions and the wires that are extending from the heart are connected to the pacemaker. Only a small skin incision that is later closed with sutures is needed to insert the pacemaker. The device remains stationary in its implanted location because of the fibrous nature of subcutaneous tissue.

The tracking ball was the only device we implanted that required surface exposure. The device worked very well under the experimental conditions, but much work needs to be done to assess the medical implications of a long-term insertion of an exposed device.

8.4.2 Device Parameters

Tissue fluid will penetrate a device that is not encased in a protective hull and affect its function. The hull's material must be carefully chosen to be pharmacologically inert and nontoxic to body tissues. For examples, pacemakers are typically made from titanium or titanium alloys, and the leads from polyether polyurethanes. *In vivo* testing would need to be carried out to determine what materials are most suitable.

The device should be as small as possible, so that it is easily implantable and cosmetically acceptable to the recipient. Functionality and minimal disruption of the contour of the skin are important considerations.

8.4.3 Risks

The main medical risk of implanting devices is infection. Infection can be caused by the procedure of implanting the devices. There are also possible risks to muscles if the device is implanted any deeper than the subcutaneous tissue. The material used for the casing could also possibly cause infections, so it will be important that the material being used passes proper testing. It is very difficult to hypothesize about other types of risks without performing testing. The wear of skin depends on the pressure applied to it; while paraplegics get sore skin from body weight resting on single spots through bones, the skin is unlikely to wear from manual pressure. The proposed input with implanted devices is short and low in force and intensity, making the skin unlikely to wear. One risk that is relatively low is that of the skin actually tearing. Skin is very strong and it is unlikely that the small devices would cause any damage. However, determining the long-term effects of interactions with implanted devices on skin requires further studies.

8.4.4 Implications and Future Studies

All of the input and output devices were functional under the experimental conditions of this study. Further cadaveric study is needed to determine if gender, skin color, and site of implantation affect device function. In the next phase, testing would also be carried out on unembalmed tissue, although the skin of lightly embalmed and unembalmed specimens is similar, loose, and pliable in both cases. Finally, the medical implications of long-term insertion of devices of this nature require detailed study.

8.5 Discussion and Limitations

The results of our study shows that traditional user interfaces for input, output, wireless communication, and powering function when embedded in the subcutaneous tissue of the forearm. Obtaining an evaluation of common components establishes the foundation for future investigations into more complex devices to explore the many other aspects of implanted user interfaces.

For example, we disregarded security concerns in our exploration. Wireless implanted devices need to prevent malicious activities and interactions from users other than the host user, such as stealing or altering stored information and manipulating the devices' operating system [32].

The processing capabilities of the devices that were implanted during the technical evaluation, as well as the *3in3out* device, require only simple processing on the microchip. More work is necessary to investigate if and how implanted devices can perform more computationally intensive operations (e.g., classification tasks using machine learning [8]) and how this affects the needs for power supply.

Social perception of implanted interfaces, both by host users as well as public perception, requires more studying. Although this has been studied with implanted *medical* devices [33], social perception of invisible and implanted *user interfaces* and devices remain to be examined.

We conducted our qualitative evaluation with participants in the summer, which is why all participants wore short-sleeve shirts. In the winter, cloth will additionally cover implanted input and output components [34] and interfere with interaction, which raises new challenges.

8.5.1 Study Limitations

Our technical evaluation comprised a single specimen. In addition, we carried out the staircase evaluations with a single participant. As such, the metrics we have collected can serve as baselines for future experimentations, but should be generalized with caution. Furthermore, our evaluation captured technical metrics

from the devices, and not human factor results. In the future, it may be interesting to have external participants interact with the implanted devices and study task performance levels.

8.6 Conclusions

The technological transition society has made in the past 30 years is astounding. Technology, and the way we use it, continues to evolve and no one can tell what the future holds. Several experts have predicted that cyborgs are coming [35, 36], and devices will become indistinguishable from the very fabric of our lives [1]. If we look at how much has changed, it should not be hard to believe that we will one day interact with electronic devices that are permanent components of our body. Our work takes a first step toward understanding how exactly this might be accomplished, and begins to ask and answer some of the important technical and human factors, and medical questions.

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