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Exploring accelerometers as a user interface in a bone conduction sound processor

A pilot study

Master's thesis in Biomedical Engineering

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Department of Electrical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018

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Cover: Finalized prototype design used in the study.

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Abstract

This study explores the possibility of using an accelerometer as a user interface in a bone conduction sound processor, which is a type of hearing device used for rehabilitation of patients suffering from conductive hearing loss, mixed hearing loss or single-sided deafness. This was done by comparing it to a push button based user interface. An accelerometer user interface could potentially have several benefits compared to a push button user interface, such as reduced size, improved water resistance and possibility to use the accelerometer for other functions, such as fall detection.

The comparison was performed through a study conducted on 16 volunteers using a prototype device featuring a user interface based on an accelerometer. The selected motions to activate the accelerometer was tapping on and turning the prototype device. The prototype was constructed using a Baha 5™ sound processor and a microcontroller based on the Arduino platform.

Given a sufficient performance increase with respect to successfully identifying input patterns and rejecting false positives, an accelerometer user interface can replace a push button user interface. However, the current prototype device has a statistically significant worse performance with regards to generating input compared to a push button based system. It was also found that given that both user interfaces have similar performance, using the accelerometer user interface and tapping the prototype is the preferred method of generating user input. Secondary conclusions of the report are that other movements, such as turning the prototype can also be used to generate user input, and that input patterns such as tapping and turning can be generated by both the preferred and non-preferred working hand without any statistically significant difference in performance. Recommendations for further studies on the topic of using accelerometers to generate user input are also proposed.

Keywords: accelerometer, push button, user interface, bone conduction sound processor, Arduino, tap, tapping.

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Lars Petersson, Gothenburg, June 2018

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Abbreviations

AC Air Conduction

BC Bone Conduction

CS Chip Select

FIFO First-in First-out
FIR Finite Impulse Response

GCP Good Clinical Practice
GMP Good Manufacturing Practice

I^{2}C Inter-Integrated Circuit
IEC Independent Ethics Committee
IIR Infinite Impulse Response

LED:s Light-Emitting Diodes
LGA Land Grid Array

MEMS Micro Electro-mechanical System
MISO Master Input Slave Output
MOSI Master Output Slave Input

PCB Printed Circuit Board

SPI Serial Peripheral Interface

UI User Interface

1
Introduction

Having a disability is often a limitation for people in today's society. Thanks to modern technology however, we are often able to fully or partially overcome disabilities through various technological aids. However, these technological aids can often be intrusive and highly visible, leading to stigmas and prejudice from the surrounding society, or difficult to use, leading to irritation and a reluctance to use by the wearer. By improving the usability of such technological aids, patient satisfaction and quality of life could be improved.

In this study the possibility of using an accelerometer to generate user input in a bone conduction sound processor will be explored and compared to the conventional method of using push buttons to generate user input. This will be done through the construction of a prototype device using an accelerometer User Interface (UI), and a following study on 16 volunteer test subjects using the prototype device.

This report will initially describe theory relevant to the thesis before describing the methods used in constructing the prototype and performing the study. The report will thereafter present the results of the study performed as well as a discussion on the results and the study in general. Finally conclusions will be presented.

1.1 Background

1.1.1 Motivation

One of several driving factors in the development of bone conduction sound processors and hearing aids is the reduction of their size and visibility. Among potential users of hearing devices, the stigma related to size and visibility of hearing devices is the main reason why users choose not to use hearing devices [1]. Reducing the size and visibility of hearing devices may therefore lead to higher patient satisfaction and quality of life. One method of reducing the size and visibility of hearing devices could be to replace the push button with a smaller accelerometer.

However, using an accelerometer-based UI could have other benefits as well when compared to a push button UI, such as increased water resistance and the possibility of using the accelerometer in other functions, such as fall detection.

1.1.2 Similar attempts

Accelerometers are used extensively for a wide variety of tasks, such as providing user input and collecting data. Common applications include tilt detection in smartphones and other devices, data collection on physical activities and fall detection in various health devices [2, 3, 4]. Patents for using accelerometers in providing user input to hearing aids have been found as well, but no application has reached the market [5].

1.2 Aims and limitations

The aim of this study is to perform a preliminary investigation into using accelerometers in general for generating user input, as well as the performance of the accelerometer used in the study. This investigation will however be limited to input patterns such as tapping onto, and rotating the accelerometer. The study will also investigate the experience of users using an accelerometer UI, and compare how well users can use an accelerometer UI with their non-preferred working hand compared to their preferred working hand. Any secondary uses of the accelerometer, such as fall detection is not included in this study. The target application for the study is a bone conduction sound processor model named Baha 5® from Cochlear Bone Anchored Solutions AB. Other applications where an accelerometer could replace a push button is not included in this study.

2

Theory

In the following sections, a short theoretical background is presented, covering the anatomy of hearing in humans and different types of hearing devices and their functions. Theory relevant to the construction of the prototype and the performed study is also presented.

2.1 Hearing

The ear is the bodily organ that is connected with hearing, one of the different senses of the human body. The ear is a complex organ that consists of many subparts. It is divided into three major regions; the external ear, the middle ear and the inner ear, illustrated below in Figure 2.1.

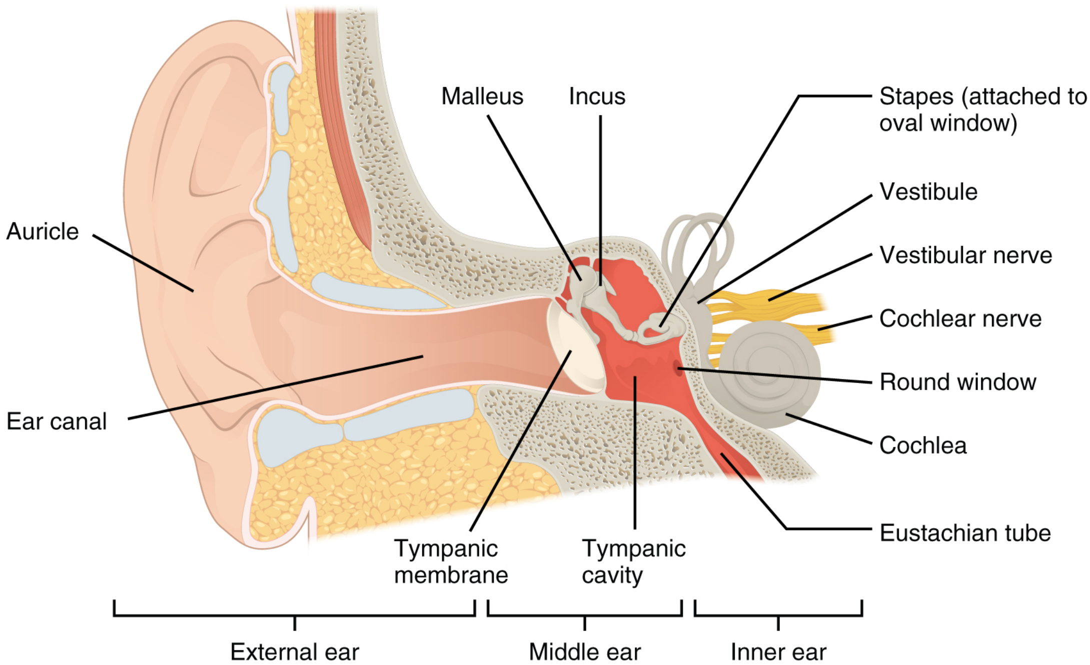

Figure 2.1: Illustration of the ears anatomy [6].

The outer ear encompasses the auricle and the ear canal, both with the function of capturing sound waves propagating through the surrounding air, and directing them towards the middle and inner ear. The ear canal also acts as a resonator, amplifying certain frequencies more than others, with a peak amplification at around 3 kHz, where the amplification in the ear canal is 10 dB compared to the sound pressure at the entrance to the ear canal [7].

The middle ear is the section that consists of the tympanic membrane and the three auditory ossicles; the malleus, incus and stapes. The function of the middle ear is to transmit the sound vibrations in the air via the ear canal into the cochlea. In this task the middle ear acts as an impedance transformer, bridging the low impedance of air with the relatively high impedance of the cochlear fluid in the cochlea. Without the middle ear performing this task, 99.9% of the energy in the air vibrations would be reflected and lost if interfaced directly with the cochlear fluid [7].

The inner ear consists of the cochlea and its subparts, as well as the balance organ. The cochlea is a spiral formed hollow bone, containing cochlear fluid and various sensory organs. The task of the cochlea is to convert the incoming vibrations into nerve signals that are conducted to the relevant parts of the brain. However, the cochlea does not only convert the vibrations coming via the middle ear, converted from the air vibrations in the outer ear. It also converts vibrations coming through the bones of the body to the cochlea. These two different sources for sound are referred to as Air Conduction (AC) and Bone Conduction (BC) [7].

AC and BC are both part of a person's normal hearing. When hearing your own voice, about half of the experienced sound comes from AC and the other half from BC, however this varies with the frequency of the spoken sound [8, 9]. When the sounds are external to the body the proportion of BC hearing becomes smaller and less noticeable, unless AC is impaired in some way, for example by ear plugs, cerumen or a hearing impairment.

2.1.1 Hearing Loss

Hearing loss is a very common disorder, affecting approximately 5% of the global population [10]. Hearing loss can be attributed to several different causes, and can come in varying degrees of severity. It is often divided into three main categories of hearing loss; conductive, sensorineural and mixed hearing loss [11].

Conductive hearing loss is attributed to causes that hinder vibrations from reaching the cochlea. This is often due to problems with the outer or middle ear. Common causes can be cerumen obstructing the ear canal or accumulation of fluid in the middle ear. While these and other causes can be remedied through various surgical procedures, others can not, for example a puncturing of the tympanic membrane.

Sensorineural hearing loss is attributed to causes originating in the inner ear or brain. This can be due to for example noise-induced hearing loss or age-related hearing loss, known as Presbycusis.

Finally there is mixed hearing loss, which is a combination of conductive and sensorineural hearing loss. Hearing loss can also be uni- or bilateral, meaning that it is either a loss of hearing on one ear or both.

Certain hearing impairments can to various degrees be treated. Some can, as stated earlier be remedied with surgical action, others will heal over time, while some can be rehabilitated with the use of medical implants [7].

2.1.2 Hearing Devices

There are several different types of hearing devices available, depending on what type of hearing loss a patient is suffering from. The most simple ones are conventional air conduction hearing devices that only amplify the sound experienced at the auricle, usually by recording the sound with one or two small microphones, amplifying it and distributing it directly into the ear canal. These conventional hearing aids come in several different forms, such as behind-the-ear, in-the-ear or completely-in-the-canal, where the names indicate the placement of the hearing aid [12].

More intricate hearing aid solutions include middle ear implants, cochlear implants, auditory brainstem implants and bone donduction devices.

Middle ear implants are implanted into the middle ear, and uses a transducer to stimulate directly onto the ossicles. This implant is suitable for patients with sensorineural hearing loss, but with a fully functional middle ear, who for some reason has had limited success with conventional air conduction hearing aids [13].

Cochlear implants rehabilitate profound sensorineural loss, when conventional hearing aids have no or little effect. A cochlear implant has one external part containing a microphone and a sound processor, that is fitted onto the outside of the head, and one internal part that is implanted into the the inner ear. The cochlear implant work by directly stimulating the hearing nerve in the cochlea by using an electrode array that is implanted in contact with the auditory nerve in the cochlea [12]. Cochlear implants are suitable when the patient has a complete loss of hearing, but still retains some functionality in the auditory nerve [14].

Auditory brainstem implant is an implant that bypasses even the auditory nerve, and stimulates directly onto the cochlear nucleus complex, using multiple electrodes to achieve a good reconstruction of normal hearing [15].

Bone conduction devices, which have been used in this report are described in greater detail in the following section.

2.1.3 Bone-conduction devices

Conductive hearing loss can be rehabilitated by bypassing the outer and middle ear through bone conduction. This is performed by attaching a device onto the head by some kind of mechanical connection to the skull bone. These devices can be sorted into different groups, shown in Figure 2.2 [16].

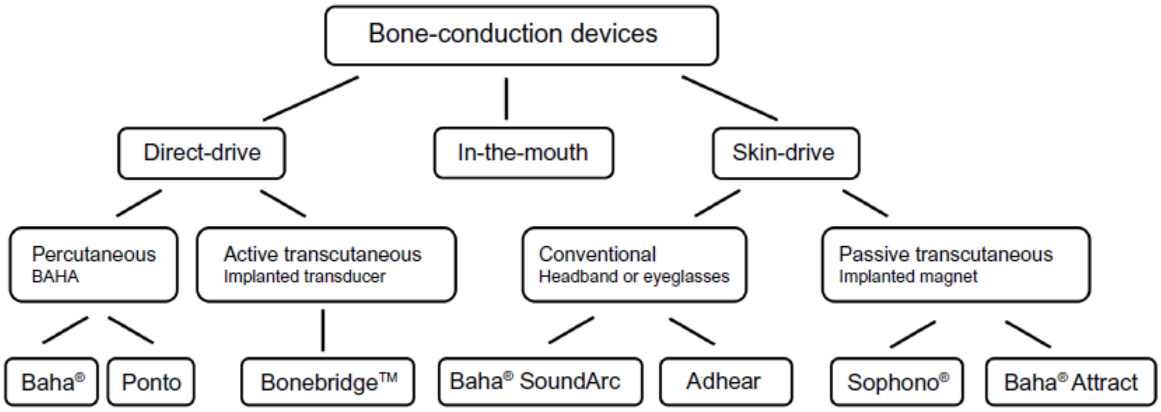

Figure 2.2: Classification of different bone-conduction devices, modified to exclude devices currently not on the market [16].

Direct-drive refers to devices with a direct mechanical connection to the skull bone, with no or very little attenuation between the transducer and the bone.

In-the-mouth refers to, as the name suggest, devices that are fitted into the mouth, often connected to the teeth. This is due to that the teeth have a very good connection with the skull bone. However, these devices are no longer available on the market.

Skin-drive refers to devices that are connected to the skull bone via the skin, and therefore have to deal with the signal attenuation caused by the skin.

The Direct-drive and Skin-drive categories can also be further divided into subcategories. The direct-drive devices can be divided into Percutaneous and Active-transcutaneous. Percutaneous devices refers to devices that are fitted with a mechanical connection to the skull, penetrating the skin. These have a very good connection to the bone with minimal attenuation, but the skin penetration can give rise to frequent skin infections, and must be cleaned every day [16]. Examples of such hearing devices are the Baha® by Cochlear Bone Anchored Solutions [17] and the Ponto by Oticon Medical [18].

Active-transcutaneous direct-drive refers to devices with a direct connection to the bone, but leave the skin intact. These devices often have one internal part and one external part. The internal part is implanted in connection to the bone and contains the transducer. The external part is then fitted on the outside of the skull with the use of a magnetic coupling to the internal part, and contains the microphone and a sound processor. The two devices then communicate wirelessly through the skin. This category has the advantage of avoiding both the issues related to skin penetration and skin attenuation, however the internal part in these devices often has a significant volume that can be a challenge to implant successfully [16]. An example of such a device is the Bonebridge™ by MED-EL [19].

Skin-drive can be divided into Conventional skin-drive and Passive-transcutaneous skin-drive. Conventional skin-drive refers to devices fitted onto the outside of the skull with some form of removable attachment, such as a headband or spectacles. These devices have the advantage of being completely non-invasive, however they have to deal with the attenuation provided by the skin, and they generate numerous complains of discomfort from patients, due to the pressure the devices have to apply to the skin to achieve a good mechanical connection [16]. Examples of such devices are the Baha Soundarc by Cochlear Bone Anchored Solutions [20] and Adhear by MED-EL [21].

Passive-transcutaneous skin-drive devices are a middle ground between conventional skin-drive and Active-transcutaneous direct-drive. They use the magnetic fitting system from the active-transcutaneous direct-drive by implanting a magnet inside the skin, but the stimulation is provided from the outside through the skin. These devices can overcome the issues with discomfort reported by users of conventional skin-drive devices, but still have to deal with skin attenuation [16]. Examples of such devices are the Sophono™ by Medtronic [22] and the Baha Attract by Cochlear Bone Anchored Solutions [23].

2.2 Signal Processing

Common to all types of electronic hearing devices are that they feature a sound processor that uses signal processing to amplify and enhance the sound experienced by the user.

Signal processing is the manipulation of signals to either extract information from, or embed information into various signals. This manipulation can be done in several different domains, such as the space-, time- or frequency domain. It can also be done on both analog and digital signals. In nature, most signals are analog, but it is often desired to perform signal processing on digital signals. This is due to digital signal processing having several advantages over its analog counterpart, such as being more flexible and having higher performance [24].

Sampling is the process of converting an analog signal into a digital one. This is performed by measuring the signal at a set number of times each second. The sampling rate is therefore a measure of how accurately the sampled signal is representing the analog signal. The sampling rate also determines the highest frequency that the sampled digital signal can contain, which is half the sampling frequency. This law is known as the Nyquist-Shannon sampling theorem [24].

2.2.1 Filtering

One way of manipulating a signal is to use filters. Filters can attenuate or amplify certain parts of the signal, depending on the type of filter. There are a multitude of filters, but common types include [24];

- Low-pass filter, which attenuates high frequencies.
- High-pass filter, which attenuates low frequencies.
- Band-pass filter, which attenuates all frequencies except those in a certain range.
- Band-stop filter, which only attenuates frequencies in a certain range.

A filter's frequency response is often used to describe its function, and describes its amplification across different frequencies. A typical frequency response for a low pass filter is shown below in Figure 2.3. Important regions shown in the figure are; the pass band, which is the range of frequencies not attenuated by the filter, the stop band, which is the range of frequencies attenuated by the filter, and the cut-off frequency, which is defined as the frequency where the attenuation reaches -3 dB [24]. Filters can be implemented both as analog and digital filters. Digital filters are one or a system of equations, while analog filters uses physical components such as resistors, capacitors, inductors and operational amplifiers to achieve the same effect [25].

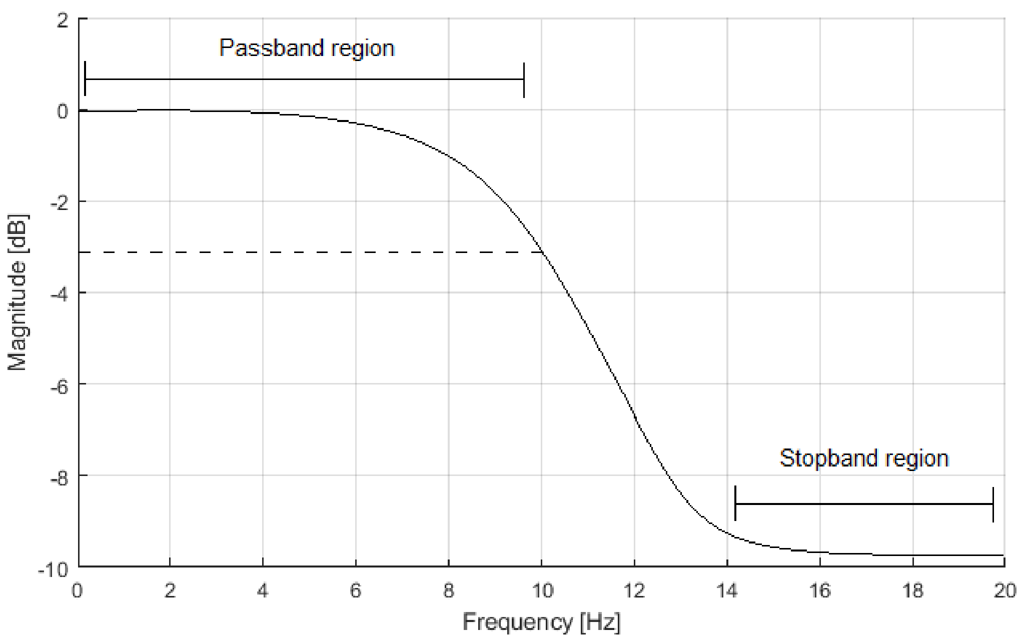

Figure 2.3: Typical low-pass filter with a cut-off frequency of 10 Hz.

2.2.2 Finite and Infinite Impulse Response filters

Filters can be sorted into two main categories, Finite Impulse Response (FIR) filters and Infinite Impulse Response (IIR) filters. They are characterized by their impulse response, in which FIR filters have an impulse response that goes to zero after a finite amount of time, and IIR filters have an impulse response which never becomes zero. This is due to the structures of the filters. The output of a FIR filter depends only on the current and past input, while the output of a IIR filter incorporates feedback, and depend on the current and past input, as well as past outputs [24].

A complete comparison between FIR and IIR filters is beyond the scope of this report, however some key differences can be noted:

- 1) For a given requirement, a FIR filter usually has to be more complex to achieve the same performance as a IIR filter.
- 2) FIR filters are always stable, whilst IIR filters can become unstable [26].

2.3 Communication in electronics

Communication between electronic devices is usually performed according to set protocols. Such communication is referred to as serial communication. Serial communication is on the bit level, which means that the information is sent as digital ones or zeros, or as high or low voltage. Communication between electronic devices is often performed between one controlling device, referred to as the master, and one or multiple controlled devices, referred to as slave devices. To be able to communicate, all devices in a communication network need to agree on the speed of communication. This is accomplished by sharing a clock signal between all devices. For the master device to be able to select which slave device to communicate which, all slave devices use a Chip Select (CS) signal, which when active tells the device that the master is talking to it.

There are two different common protocols, Serial Peripheral Interface (SPI) and Inter-Integrated Circuit (I^2C). The two protocols function according to the principles described above, both using a shared clock signal and a CS signal, but there is a difference in connection setup between the two protocols. SPI uses two dedicated connections for serial data, one Master Output Slave Input (MOSI) and one Master Input Slave Output (MISO). The MOSI is used to send control signals to the slave device, and the MISO is used to send data signals back to the master. The I^2C protocol in comparison only uses one connection for serial data, on which both control signals and data signals are sent back and forth.

This difference between the protocols results in that SPI is faster than I^2C, able to transmit data at a higher bit rate, but I^2C uses less hardware connections [27, 28, 29].

2.4 Performing patient testing

Performing tests on human subjects is regulated by different laws in different countries. However, most of these laws originate from the same source, the Good Clinical Practice (GCP) standard. GCP is an international standard on how to conduct ethical research released in 1996 by the International Conference of Harmonization. There are several other documents relevant to the field, such as the Declaration of Helsinki, but GCP has become the universally accepted standard for ethically performing trials on human subjects [30]. GCP in itself does not compromise any legally binding laws, but countries are encouraged to implement their own regulations building on GCP. The following section will elaborate on what GCP compromises.

2.4.1 Good Clinical Practice

GCP consists of 13 principles, outlined below [31].

- Clinical trials should be conducted in accordance with the ethical principles that have their origin in the Declaration of Helsinki and that are consistent with GCP and the applicable regulatory requirement(s).
- Before a trial is initiated, foreseeable risks and inconveniences should be weighed against the anticipated benefit for individual trial subjects and society. A trial should be initiated and continued only if the anticipated benefits justify the risks.
- The rights, safety, and well being of trial subjects are the most important considerations and should prevail over the interests of science and society.
- The available nonclinical and clinical information on an investigational product should be adequate to support the proposed clinical trial.
- Clinical trials should be scientifically sound, and described in a clear, detailed protocol.
- A trial should be conducted in compliance with a protocol that has received prior Independent Ethics Committee (IEC) approval.
- The medical care given to, and medical decisions made on behalf of subjects should always be the responsibility of a qualified physician or, when appropriate, of a qualified dentist.
- Each individual involved in conducting a trial should be qualified by education, training, and experience to perform his or her respective task(s).
- Freely given informed consent should be obtained from every subject prior to clinical trial participation.
- All clinical trial information should be recorded, handled, and stored in a way that allows its accurate reporting, interpretation, and verification.
- The confidentiality of records that could identify subjects should be protected, respecting the privacy and confidentiality rules in accordance with the applicable regulatory requirement(s).
- Investigational products should be manufactured, handled, and stored in accordance with applicable Good Manufacturing Practice (GMP). They should be used in accordance with the approved protocol.

- Systems with procedures that assure the quality of every aspect of the trial should be implemented.

2.4.2 Independent Ethics Committee

An IEC has, according to GCP, the responsibility to safeguard the rights, safety and well-being of all trial subjects. What constitutes an IEC is defined in GCP as following [31]:

The IEC should consist of a reasonable number of members, who collectively have the qualifications and experience to review and evaluate the science, medical aspects, and ethics of the proposed trial. It is recommended that the IEC should include:

1. At least five members.
2. At least one member whose primary area of interest is in a nonscientific area.
3. At least one member who is independent of the institution/trial site.

2.4.3 Regulation in Sweden

In Sweden the role of an IEC is fulfilled by the Centrala Etikprövningsnämnden, and its six regional offices in Stockholm, Gothenburg, Uppsala, Linköping, Umeå and Lund. These are the agencies that oversee and approve scientific studies. According to Swedish law, a scientific study requires approval if it fulfills any of the following:

- Gathers sensitive personal information (information that concerns race or ethnic origin, political views, religious or philosophical views, membership in a union or information that concerns health or sex life).
- Involves a physical operation on the research subject or uses a method designed to affect the subject physically or mentally.
- Is carried out on biological material that has been taken from a physical person and can be traced to that person.

Of further note is that student studies do not need to seek ethical approval according to Swedish law [32].

3
Methods

To evaluate the feasibility of using an accelerometer to generate user input, a prototype device was developed to be used for studying both how well the given implementation worked, and how users responded to using a accelerometer UI instead of a push button UI. The first of the following sections will describe the details of the prototype and its design. The second section will describe the filtering and software used in the prototype. The third section will describe the design of the study performed.

3.1 Prototype design

3.1.1 Accelerometer description

The used accelerometer is a Micro Electro-mechanical System (MEMS)-type accelerometer. It measures forces in the x-, y- and z-directions by measuring the capacitive difference between a few small metal wires. When the wires experience an acceleration in a certain direction, the distance, and thereby the capacitance between them changes, which is then measured and converted to a voltage difference [33]. The signal generated by the capacitive difference between the wires is amplified and converted into a digital signal, which is then processed and stored in the Control Logic block awaiting to be read. The block diagram for the accelerometer can be viewed below in Figure 3.1.

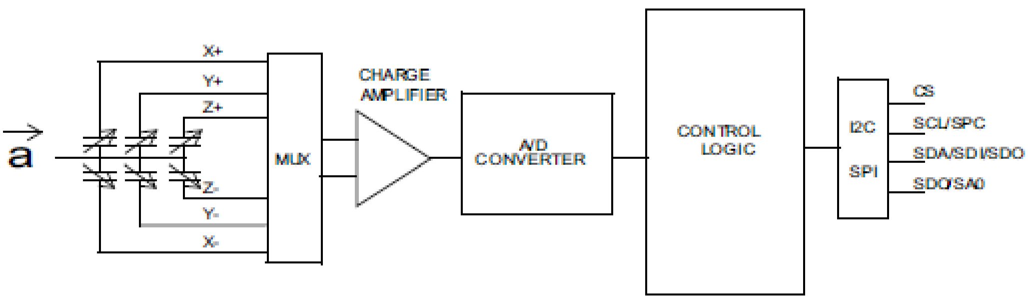

Figure 3.1: Block diagram showing internal function of the accelerometer.

The accelerometer is a 2x2x1 mm Land Grid Array (LGA)-package. It needs to be connected with three decoupling capacitances, two 100 nF and one 10 μF. Using surface-mounted capacitors, these components can be as small as 0.6x0.3x0.25 mm and 1.0x0.5x0.35 mm, giving the accelerometer and the required surrounding circuitry a total potential smallest volume of 4.22 mm^2.

The accelerometer includes multiple settings and features that can be used to control it and achieve various outputs. Important settings include:

- Mode: Low-power mode, Normal mode and High-Resolution mode. Controls number of bits of resolution in the measured data, 8-, 10- or 12-bit resolution. This has a high impact on power consumption.
- Sampling frequency: Possible choices are 5376 Hz, 1620 Hz, 400 Hz, 200 Hz, 100 Hz, 50 Hz, 25 Hz, 10 Hz and 1 Hz. 5376 Hz is only available in low-power mode however. This has a high impact on power consumption.
- First-in First-out (FIFO) mode: The accelerometer features a First-In-First-Out buffer, which enables the accelerometer to save up to 32 x, y and z values in a buffer that can be read at will. This allows for the controller to access the output of the accelerometer less often, resulting in less communication between controller and accelerometer, and thereby a lower power consumption on the controlling side.
- I^2C/SPI mode: Controls which communication protocol to follow in the communication between controller and accelerometer.
- High-pass filter mode: The accelerometer features an internal high-pass filter that can be used to filter out low frequency components.
- Scale selection: The scale of the output can be varied between $\pm 2g$, $\pm 4g$, $\pm 8g$, $\pm 16g$.

Since the accelerometer might be used constantly, a low power consumption is very desirable. As can be seen above, several different settings affect the power consumption. Firstly, the accuracy of the acceleration measurements are of no particular interest in this application, only magnitude differences are important. Therefore, low-power mode should be utilized, which will reduce the power consumption compared to normal- and high-power mode. Secondly, the sampling rate should be kept as low as possible, and investigating how low sampling rate can be used has been a major part of this thesis.

3.1.2 Hardware Design

It was deemed of high importance to evaluate the accelerometer performance in a setting as close to a real one as possible. A Baha 5 bone conduction sound processor was therefore chosen as the target technology to implement the accelerometer in. To accomplish this, a Printed Circuit Board (PCB) featuring the accelerometer was designed and placed inside a Baha 5 shell containing only the transducer to replicate the weight and handling of an actual Baha 5. The PCB measured 8.25 x 5 mm and featured besides the accelerometer, two pull-up resistors and three decoupling capacitors, with five pads for connections to the microcontroller. Due to the size limitations I^2C was chosen as the communication protocol. The PCB design is shown in Figure 3.2.

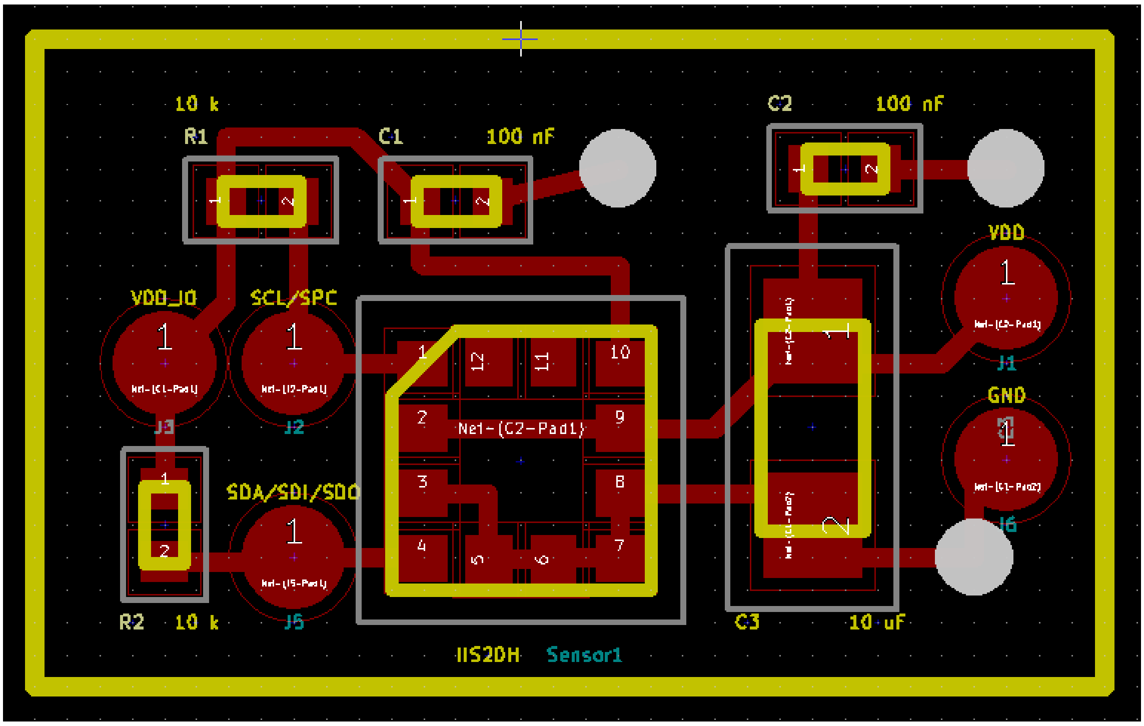

Figure 3.2: PCB design used in test setup.

A suitable microcontroller was then chosen to control the accelerometer. Due to cost and ease of implementation, Arduino (Arduino, Somerville, USA) was chosen as the implementation platform, and an Adafruit Feather M0 Adalogger was chosen as the microcontroller used. This choice was due to the low cost of the microcontroller, as well as its capability of datalogging.

The Baha 5 shell was then attached to a Cochlear Baha Softband™, which could be worn by participants in the study, while the microcontroller was placed in a box, attached to the Baha 5 shell with a wire long enough for the subject to be able to hold the box in their hand. Light-Emitting Diodes (LED:s) were mounted on the box, and their activation were tied to successful recognition of different distinct input patterns, described in greater detail in the next section. This provided visual feedback on accelerometer activation to the subject. The final design of the prototype is shown in Figure 3.3. The final weight of the prototype was 9.5 grams, excluding the controller box and the cable, compared to the weight of an actual Baha 5 which is 10 grams.

Figure 3.3: Finalized prototype.

3.2 Filtering and software design

3.2.1 Accelerometer data analysis

Using the prototype, accelerometer data was gathered containing both artificially generated noise and various user-generated patterns. An example of such data containing only taps and no artificial noise can be seen below in Figure 3.4, where the data has been normalized around 0. The artificial noise was generated by tilting, turning, sweeping and mildly shaking the prototype, while the user-generated patterns consisted of tapping the prototype. The taps were performed as similarly as possible, but still generated different responses from the accelerometer, as can be seen in Figure 3.4.

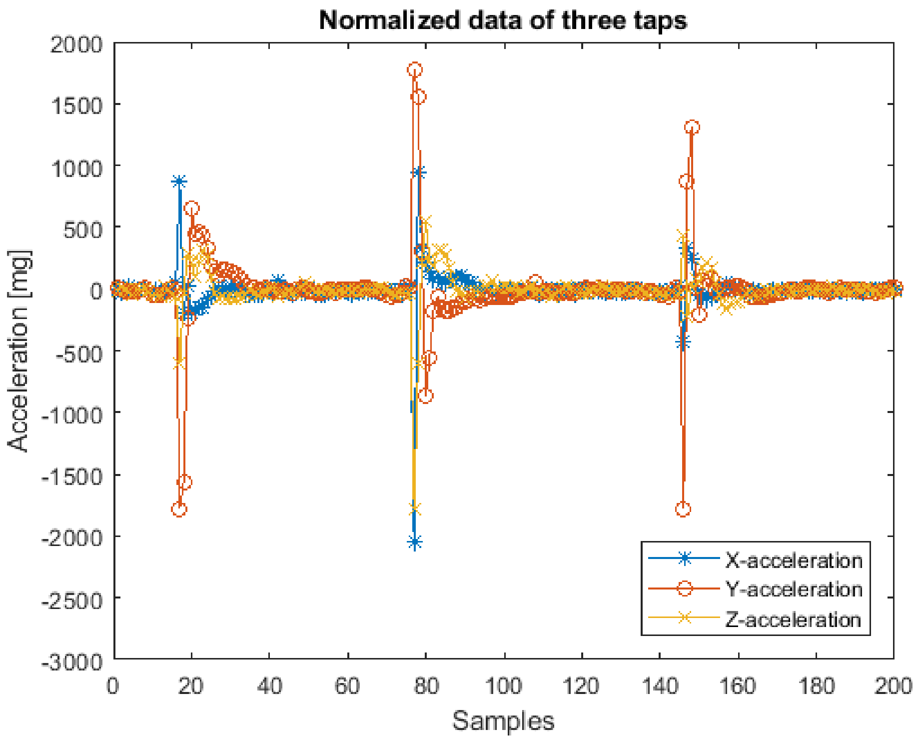

Figure 3.4: Raw acceleration data generated from three taps on the prototype.

The data was analyzed with regards to mean value, variance and frequency content. The only metric that differed significantly between the noise and user-generated patters was the frequency content of the signal. When tapping onto the prototype, the generated signal contained more high frequency energy than the signal containing artificial noise. This can be seen in Figure 3.5, where the accelerometer's highest sampling frequency has been used to analyze the frequency content of two signals, one containing noise and one containing three taps on the prototype.

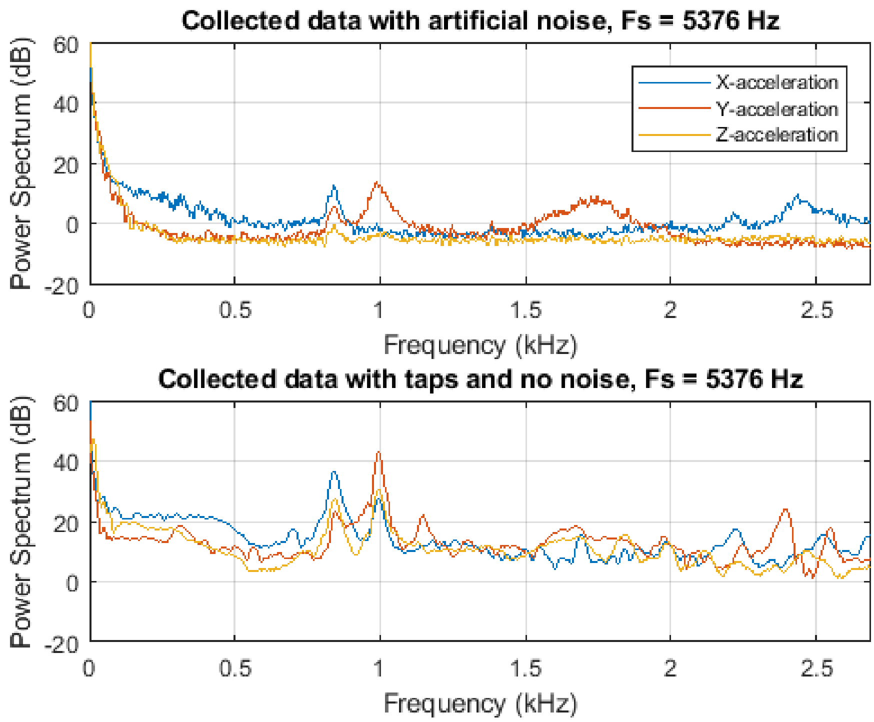

Figure 3.5: Spectral analysis of accelerometer data, Fs = 5376 Hz.

Here it can clearly be seen that two strong frequencies are generated around approximately 800 and 1000 Hz. However, in the interest of having a low power consumption, the sampling rate of the accelerometer should be kept as low as possible, which would prevent these relatively high frequency peaks to be detected. By analyzing the frequency content of the gathered data at lower sampling frequencies, there is still a magnitude difference between the high frequency content of the signal with taps and the signal without, which can be seen in Figures 3.6 and 3.7, where sampling rates of 200 Hz and 100 Hz have been used.

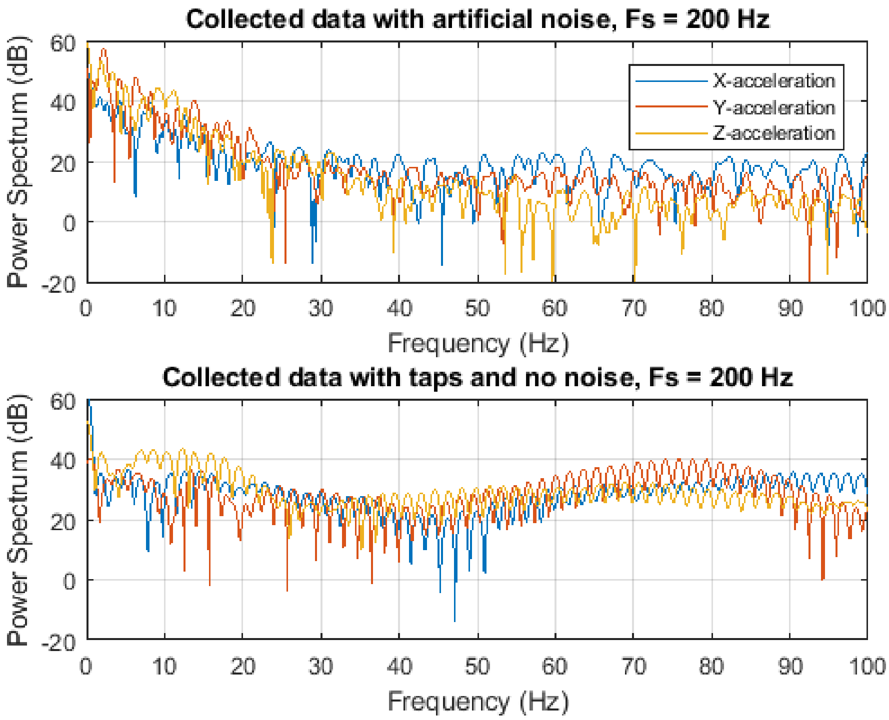

Figure 3.6: Spectral analysis of accelerometer data, Fs = 200 Hz.

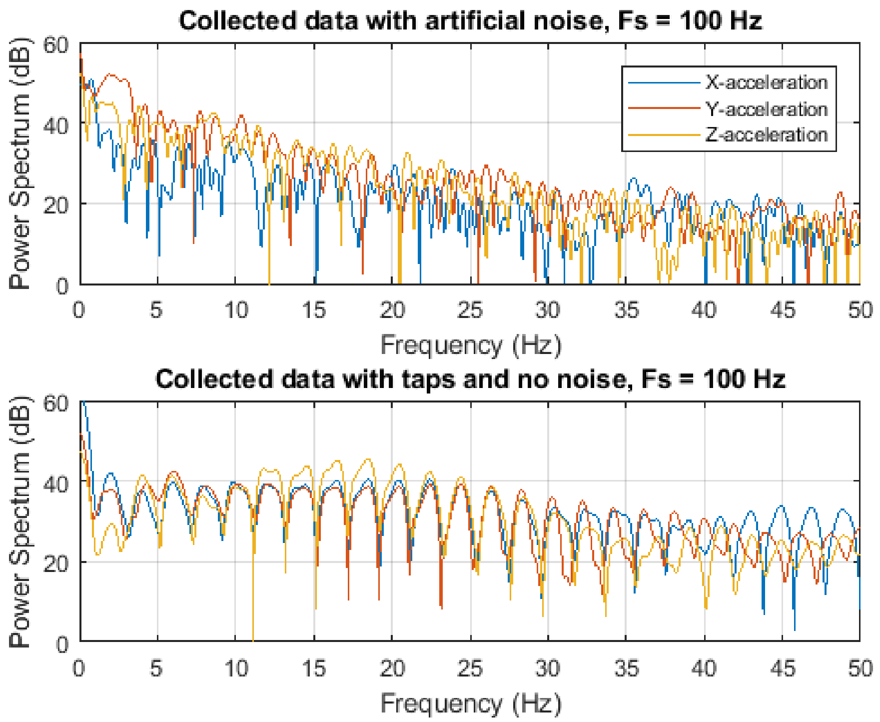

Figure 3.7: Spectral analysis of accelerometer data, Fs = 100 Hz.

Going further down in sampling frequency, it can be seen that there is still a magnitude difference between noise and taps at 50 Hz in Figure 3.8, but not at 25 Hz in Figure 3.9. This means that in theory, the approach of analyzing the frequency content of a signal to determine if there are taps in it should work for as low sampling frequency as 50 Hz.

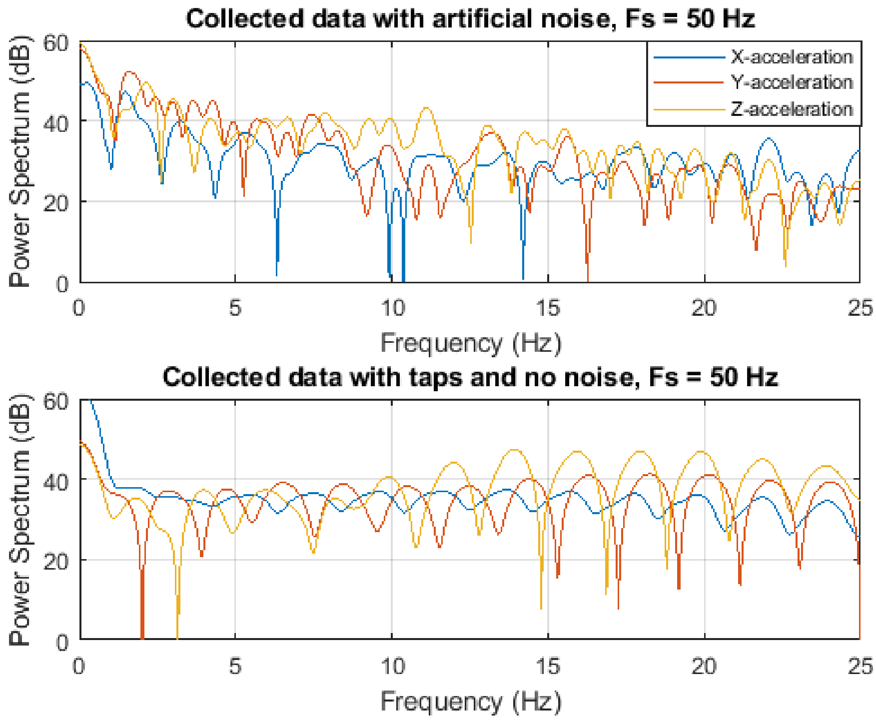

Figure 3.8: Spectral analysis of accelerometer data, Fs = 50 Hz.

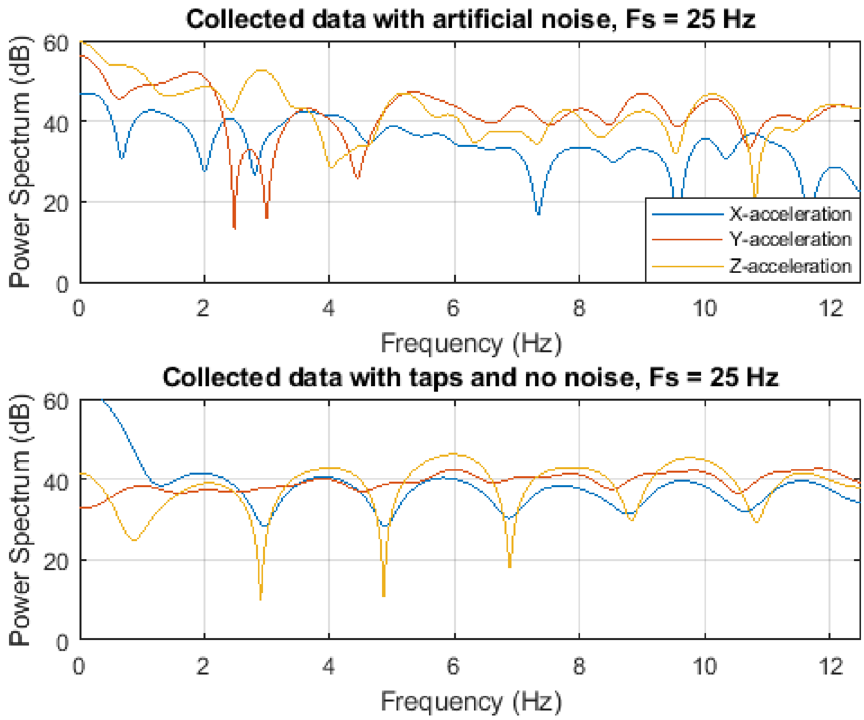

Figure 3.9: Spectral analysis of accelerometer data, Fs = 25 Hz.

Using a high pass filter, it should therefore be possible to differentiate the high frequency content from the low frequency content, and thereby determine if a signal contains a tap or not.

3.2.2 Filter design

To show that the accelerometer can be used to provide user input, it was chosen that five distinct input patterns would be tested. These distinct patterns was one, two and three taps on the prototype, as well as turning it 90° either forwards or backwards. To implement this, the raw accelerometer data was processed using digital filters.

To filter out the low frequency noise generated by moving the accelerometer, a 1st order IIR high pass filter was used. Two different versions of the filter were used in the study, one with a cut-off frequency of 0.1 Hz and one with 7.5 Hz. Using two different cut-off frequencies for the high pass filter in the prototype had the effect of using two different sensitivity settings for the tapping function. Using a lower cut-off frequency had the effect of the prototype registering more taps, but also more false positives, while using a higher cut-off frequency had the effect of the prototype being less sensitive to taps but also less sensitive to false positives. The IIR filter was selected due to its ease of implementation and low computational cost. Frequency response plots for both filters can be seen below in Figures 3.10 and 3.11. These filters worked well for a sampling rate of 100 Hz, but were not suitable for 50 Hz. This report has been unable to implement a functioning solution for a sampling rate of 50 Hz, but it might be feasible with a more advanced filtering function. The sampling frequency used in the finalized prototype was therefore 100 Hz.

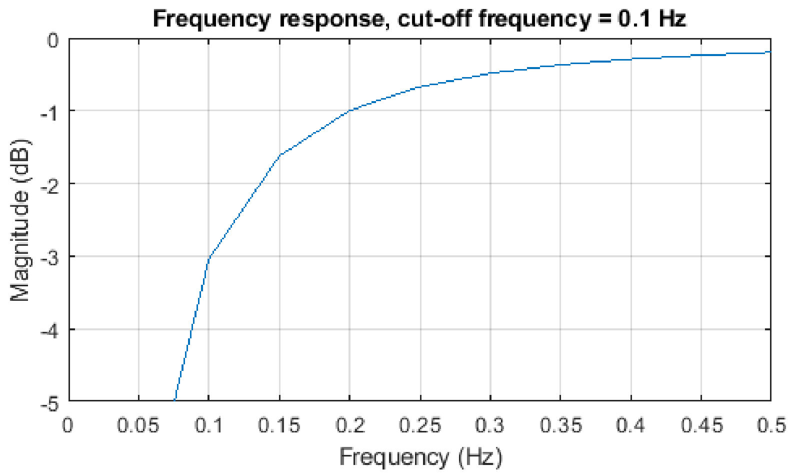

Figure 3.10: High pass filter with 0.1 Hz cut-off frequency.

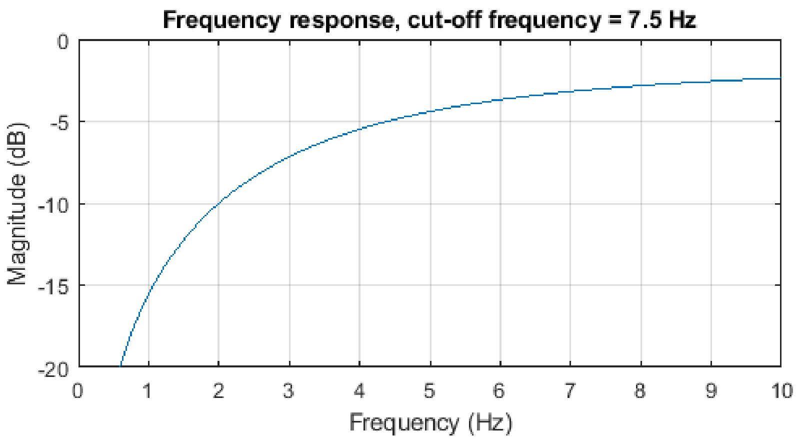

Figure 3.11: High pass filter with 7.5 Hz cut-off frequency.

A low pass filter was also implemented to better discern directional information from the accelerometer data, by filtering away any high frequency movements and only leave low frequency directional information behind. The frequency response for the low pass filter can be seen in Figure 3.12.

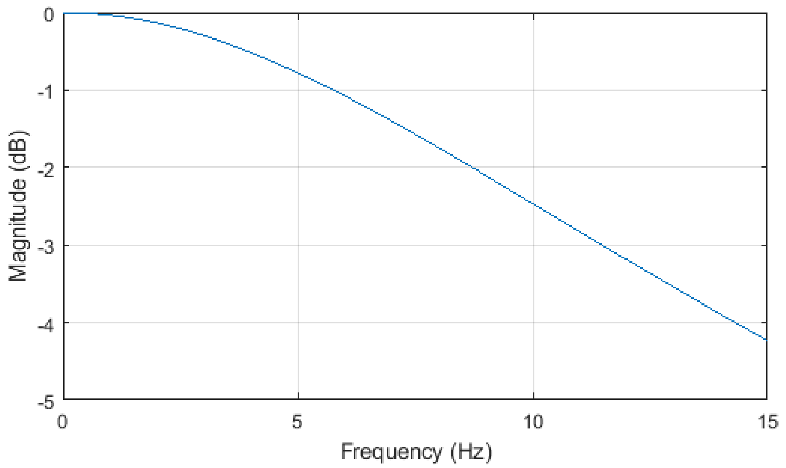

Figure 3.12: Low pass filter with 11.5 Hz cut-off frequency.

The low pass filtered data was used to detect when the prototype was turned more than 90° in any direction, and implement the turning function. The raw accelerometer data was therefore passed through the high- and low pass filter separately, and used to implement the corresponding functions, as shown in Figure 3.13

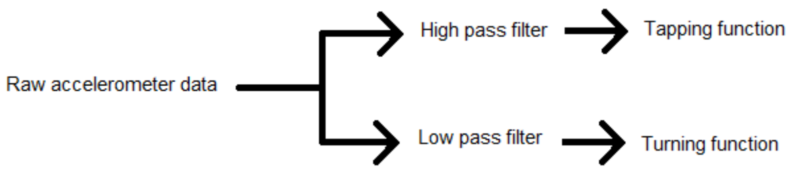

Figure 3.13: Data path of accelerometer data in prototype.

3.2.3 Software

The software script on the microcontroller was written in the Arduino Integrated Development Environment, which is a mixture of the C and C++ programming languages, with some functions unique to the Arduino platform as well [34]. The script starts by loading necessary settings onto the accelerometer that control the sampling frequency, resolution and enables FIFO mode. The script thereafter utilizes the ability to poll the number of available samples in the accelerometer. When the number of available samples are 10 or more, the scripts reads the samples, filters them through the high pass filter and iterates through the filtered values looking for peaks over a certain threshold. If any values exceed the threshold, LED:s are triggered and the number of available samples in the accelerometer are reset to zero.

3.3 Study Design

3.3.1 Data collection

The study was designed to evaluate both the performance of the accelerometer UI with the given implementation, as well as the subject's experience of using it. The data collected consisted of whether the subjects were able to successfully activate the LED:s through tapping on and turning the prototype, as well as two questions on the two different kinds of input patterns, taps and turns. The attempts were recorded as either a success or a failure, and comments from both the investigator and the subjects were noted. The preferred working hand of the subject was also noted.

The study consisted of four different parts, and before the first part, the subjects were given 2 minutes to familiarize themselves with the prototype and its functions. This was done in an attempt to lessen the impact of the learning rate involved in tapping on the results.

For the first two parts the prototype was fitted on the right side of the head, and for the two last parts it was fitted on the left side of the head.

1) The first part involved to activate single taps, double taps, triple taps and the turning function ten times each, using the more insensitive filter with the higher cut-off frequency.

2) In the second part, the cut-off frequency of the high pass filter was changed to the lower frequency, and thereby the sensitivity of the prototype was increased. This time only the single-, double- and triple times were tested, since the cut-off frequency for the high pass filter has no impact on the performance of the turning function.

3) In the third part, the prototype was switched to the left side of the head, and the subject was asked to repeat the 10 single-, double- and triple taps a third time, but now using their left hand. This was to see if the success rate differed between using the preferred versus the non-preferred working hand. The cut-off frequency was kept to the lower option.

4) In the fourth and final part, the subject was asked to walk down and up a stone staircase consisting of 24 steps, using the lower cut-off frequency still. This was to investigate whether or not it would trigger false positive signals.

The study was concluded by the subject answering two questions relating to their experience on using the prototype. The first question was to compare the action of tapping on the prototype with the action of pushing the button on the Baha 5. They were asked to answer on a scale of 1 to 5, where an answer of 5 meant that they would prefer the tapping, 1 meant that they would prefer the push button and 3 would mean that they had no preference between tapping or using the push button.

The second question regarded the action of turning the prototype more than 90°, where they were asked to grade on a scale from 1 to 5 what their experience of performing the turning motion was; 1 if they strongly disliked the movement and would prefer not to use it, and 5 is they liked the movement and would want to use it. The complete answer sheet can be seen in Figure 3.14

	Single taps	Double taps	Triple taps	Turn forward	Turn backward
Success rate with insensitive setting on right side					
Success rate with sensitive setting on right side					
Success rate with sensitive setting on left side					
No. of false positives walking in stair					

Question 1:					
How did you rate the experience of tapping on the prototype compared to pushing a button on the Baha 5? Please rate your experience from 1-5.					
1	2	3	4	5	

Question 1:					
How did you rate the experience of turning the prototype? Please rate your experience from 1-5.					
1	2	3	4	5	

Figure 3.14: Answer sheet for the performed study.

3.3.2 Good Clinical Practice Compliance

The test was performed according to a protocol template provided by Cochlear, which was in compliance with GCP. This protocol included inclusion and exclusion criteria for the test subjects, work instructions and a clinical risk analysis. No sensitive personal information was gathered, and subjects volunteered by answering an email that was sent out to every employee at the company. An application for ethical approval was not submitted, since it was not required due to that it was a student study.

4 Results

4.1 Data Analysis

The collected data in the study is shown below in Table 4.1. The data is collected from 16 test subjects, with a mean age of 36.81, an age distribution of 25 to 53 and a gender distribution of 11 males and 5 females. 15 out of the 16 participants preferred working with their right hand, and only one preferred to work with their left hand.

The two questions posed in the study were concerning the personal opinion on the two new UI:s compared to the old push button UI. The first question regarded the experience of tapping on the prototype instead of using the push button, and had a mean answer of 3.88 and a median of 4. The second question, regarding the experience of turning the prototype had a mean answer of 2.88 and a median of 3. This is shown in Table 4.2. Hence, the subjects were mostly in favour of the tapping function compared to the push button, but slightly in favour of the push button if compared to the turning function.

Wilcoxon signed-rank tests were performed between all single-, double- and triple tap data and simulated push button data, where it was assumed that a similar test with a push button would have a 100% accuracy. The results were p-values ranging from 3.05×10^{-5} to 0.002, which is below the chosen threshold of 0.05 for statistical significance. The null hypothesis, that the tapping data and push button data had no statistically significant difference between them therefore had to be rejected. Wilcoxon signed-rank tests were also performed between the data from the turning function and push button data, which resulted in p-values of 6.10×10^{-5} and 0.0039 for forwards and backwards respectively. Also here, the null hypothesis that there would be no difference between the turning function generated data and the push button data had to be rejected.

Table 4.1: Collected data of successful and unsuccessful accelerometer activation attempts.

Test subject	Gender	Age	PreferRed working hand	Success rate with insensitive setting			Success rate with sensitive setting right side			Success rate with sensitive setting, left side			Success rate turning		No. of false positives in stair	Grade for tapping function	Grade for turning function
				Single tap	Double tap	Triple tap	Single tap	Double tap	Triple tap	Single tap	Double tap	Triple tap	Forward	Backward			
1	M	53	R	8/10	8/10	9/10	10/10	10/10	10/10	10/10	10/10	10/10	2/5	2/5	0	4	3
2	F	25	R	8/10	10/10	8/10	10/10	9/10	8/10	9/10	10/10	10/10	4/5	5/5	1	4	3
3	M	26	R	8/10	8/10	6/10	8/10	8/10	8/10	8/10	9/10	7/10	4/5	5/5	1	5	2
4	M	43	R	9/10	6/10	6/10	9/10	7/10	5/10	10/10	9/10	4/10	3/5	5/5	5	5	3
5	F	35	R	8/10	5/10	8/10	4/10	9/10	7/10	8/10	7/10	10/10	3/5	3/5	7	4	4
6	F	46	R	8/10	5/10	3/10	10/10	7/10	6/10	9/10	7/10	7/10	4/5	3/5	5	4	2
7	M	34	R	7/10	6/10	2/10	10/10	7/10	7/10	7/10	6/10	8/10	4/5	3/5	0	4	2
8	F	28	R	9/10	9/10	5/10	10/10	8/10	9/10	10/10	10/10	10/10	4/5	5/5	3	4	1
9	M	44	R	9/10	8/10	8/10	10/10	9/10	8/10	9/10	10/10	9/10	4/5	5/5	7	3	5
10	M	25	R	7/10	4/10	8/10	7/10	5/10	6/10	6/10	9/10	5/10	5/5	3/5	7	4	3
11	F	25	L	7/10	8/10	6/10	9/10	5/10	7/10	9/10	8/10	7/10	2/5	5/5	1	4	3
12	M	44	R	8/10	4/10	3/10	9/10	9/10	8/10	8/10	7/10	6/10	3/5	5/5	5	3	1
13	M	35	R	7/10	3/10	5/10	7/10	5/10	4/10	10/10	5/10	7/10	2/5	3/5	6	4	1
14	M	34	R	8/10	7/10	9/10	8/10	8/10	4/10	7/10	9/10	9/10	3/5	2/5	4	2	5
15	M	32	R	7/10	6/10	6/10	8/10	7/10	5/10	7/10	4/10	8/10	4/5	3/5	5	4	5
16	M	30	R	8/10	6/10	3/10	10/10	8/10	5/10	10/10	7/10	6/10	5/5	5/5	7	4	3
	5F/11M																
Mean rate		36.81		0.79	0.64	0.59	0.87	0.76	0.67	0.86	0.79	0.77	0.70	0.78	4	3.88	2.88
Median rate		35		0.8	0.6	0.6	0.9	0.8	0.7	0.9	0.85	0.75	0.8	0.8	5	4	3

The single-, double- and triple tap data were also compared against each other using Wilcoxon signed-rank tests. This resulted in the data shown below in Table 4.3. Here it can be seen that there is a statistically significant difference between using the insensitive and sensitive setting in five out of the six comparisons. It can also be seen that there is no statistically significant difference between using the tapping function on the right side compared to the left side of the head in two out of three cases. To generalize this result for a comparison of tapping with preferred and non-preferred working hand, the data was rearranged and tested according to preferred working hand, which also showed no statistically significant difference between tapping with preferred or non-preferred working hand in two out of three cases.

	Mean answer	Median answer
Experience of using tapping function when compared to using a push button	3.88	4
Experience of using turning function	2.88	3

Table 4.2: Mean and median answer rate to questions in study.

	Single tap	Double tap	Triple tap
Insensitive setting compared to sensitive setting, left side	0.022	0.0018	0.0066
Insensitive setting compared to sensitive setting, right side	0.021	0.011	0.14
Sensitive setting right side compared to left side	0.75	0.26	0.034
Sensitive setting preferred side compared to non-preferred side	0.75	0.55	0.034

Table 4.3: p-values of Wilcoxon signed-rank test of tapping data.

The comments given by the subjects and the investigator during the study can be summarized as follows:

- Subjects with long hair complained that the hair was an obstruction during both tapping and turning attempts.
- Subjects appreciated that the tapping function was quick movement that required fewer fingers than using a push button.
- Some subjects were aided by the spring noise generated by the Softband attachment while turning the prototype. (A small clicking noise could be heard when the prototype was turned more than 90° forwards or backwards, generated by the attachment to the Softband.)
- Some subjects experienced a better performance while tapping on certain locations on the prototype.
- Some subjects gave the turning function a higher grade with the remark that it should perhaps not be a function used very often, but reserved for infrequent use.
- One subject expressed concerns that the turning function might feel awkward when used on an abutment.
- One subject felt that turning the prototype 90° was too much, and would rather perform a smaller turning motion.
- One subject reported that the turning function was more difficult using the non-preferred working hand.
- One subject would rather turn the prototype forwards than backwards.
- One subject reported difficulties with locating the prototype when tapping.
- One subject gave a lower grade for the tapping function due to appreciating the tactile feedback of the push button.
- The number of false positives generated depended heavily on walking style. A heavier walking style generated more false positives.
- For some subjects the result could have been greatly improved if allowed to practice with the prototype for some additional time.

The comments given by subjects with long hair motivated a comparison of the performance of the male and female participants. This was performed using Wilcoxon rank-sum test, and resulted in p-values ranging from 0.14 to 0.99, indicating no statistically significant difference between the performance of male and female participants. However, not all female test subjects had long hair, but since hair length was not noted in the study a comparison between the male and female participants was the only test available to investigate the effect of hair length on the results.

5

Discussion

5.1 Results

The collected data presented in the Results section was analyzed in two different aspects. First, it was analyzed against a hypothetical similar study using a push button UI instead of a accelerometer UI. It was assumed that such a study would have achieved 100% accuracy in recognizing input patterns. It is however not certain that such a study actually would have received such a result. Due to misclicks or not finding the push button, the actual result could have been slightly lower than 100%, which would only be advantageous to the result of the study performed in this report. It is therefore reasonable to assume that the result of the statistical test is a worst-case scenario comparison in that aspect.

The result of the Wilcoxon signed rank test between the hypothetical push button data and the accelerometer data was below the chosen level of significance, which was $\alpha = 0.05$, for each test. However, a lower level for significance could be used if the argument would be made that an accelerometer UI does not have to reach the same performance level in user input recognition as a push button. In that case, the first categories of data that would not be rejected by such a test would be the single tap categories, since they had a overall better performance than for the double and triple taps, as shown in Table 4.1. This is as expected, since single taps are a less complicated pattern than double and triple taps.

Secondly the different categories of collected data was tested against each other. These results showed several interesting notes. The first two comparisons were between using the insensitive and the sensitive setting on the left and right side of the head. These p-values were below the level required for statistical significance in five out of six cases. The high p-value achieved in the sixth category is believed to be due to chance. It is therefore concluded that these tests show that there is a statistically significant difference between using the two different sensitivity settings for the filter in the prototype device. However, a more sensitive filtering solution should also lead to an increase in false positives, and therefore a final solution used in an actual commercial product might need to make a trade-off between having a high accuracy in recognizing input patterns and rejecting false positives. In this prototype, that trade-off was determined by the choice of cut-off frequency and threshold value for peak detection. Further research would be needed to determine what an acceptable rate between recognizing input patterns and rejecting false positives would be.

A comparison was also performed between using the preferred and non-preferred working hand, and this achieved p-values over the level required for statistical significance in two out of three cases, with the last case being slightly below the level for statistical significance. It is therefore concluded that the prototype can be used with both the preferred and non-preferred working hand without any major difference in performance.

Furthermore the study has shown that there are issues related to users with long hair. This was mainly the case when it came to turning the prototype, but some subjects with long hair also had issues in tapping. A Wilcoxon rank-sum test was therefore performed comparing the performance of male and female participants in the study. While the statistical test showed no statistically significant difference in the performance between male and female participants in the study, further research on the impact of long hair on using an accelerometer UI might be warranted.

Student's t-test was also used to analyze the results in parallel with the Wilcoxon signed-rank test, even though the latter is more suitable as an analysis tool since the t-test assumes that the data is normally distributed, which the data from the study is not. However, the t-test resulted in the same conclusions as the Wilcoxon signed-rank test.

5.2 Main issues

The constructed prototype is a first implementation of an accelerometer UI, and is far from optimal. In the construction of the prototype device and the performance of the study, a few major issues with the accelerometer UI concept have been identified. The first major issue is that when using a low sampling rate and low resolution in the recorded data, the recorded acceleration values can differ substantially between input patterns that are identical. Two taps that from the user perspective appear identical in direction and force can be recorded very differently by the accelerometer, having very different magnitudes and proportions between the x-, y- and z-directions, as shown in Figure 3.4. It is therefore necessary to make a trade-off between having a low sampling rate and low resolution in the recorded data, which provides a low power consumption, and having a sufficiently high sampling rate and resolution so that the used pattern recognition algorithm have accurate data to analyze.

The second major issue is that an accelerometer is a very good instrument to detect movement, but not a very good instrument to differentiate different movements. The taps used as movement in this study can be very difficult, or perhaps even impossible, to differentiate from other movements. In the performed study, it could be seen that simply walking in the stairs generated false positives. Other movements such as shaking the head, receiving forces directed towards the head, or running, would most likely have generated even more false positives, since they are either closer to the hearing aid or have a greater impact on the body than walking in the stairs.

This issue could be solved in at least two different ways. First, attempts could be made to use the accelerometer with more complicated movements, such as moving the head in a certain way. This could reduce the amount of false positives, but could also be much more difficult for users to perform. The second solution could be to investigate more advanced filtering solutions. The currently used solution is a basic filter, and a significant effort could be directed towards finding a more suitable filtering solution.

5.3 Similarity of prototype device to real bone conduction sound processor

The prototype device was designed to be as similar to an actual Baha 5 as possible, but had a small weight difference compared to a Baha 5. The Baha 5 weighs 10 grams, while the prototype, excluding the handheld controller box weighed 9.5 grams. However, this 5% difference is so small that its impact on the result of the study was deemed to be negligible.

A larger source of difference is the method of fastening the prototype to the head. In the study, it was worn with a Cochlear Baha Softband on the head, which provides a loose connection to the head compared to an abutment. It is therefore reasonable that using the prototype with an abutment would improve the result further, since the abutment would most likely provide a harder fastening and mechanical response compared to using a Cochlear Baha Softband.

5.4 Design choices in prototype design

Several choices were made in the design of the prototype used in the study. The chosen filter cut-off frequencies, 0.1 and 7.5 Hz were chosen through experimentation. Looking at the filter content graphs displayed in Section 3.2.1, it might seem that a higher cut-off frequency such as 10-20 Hz would be more suitable. However, through experimentation it was determined that a higher cut-off frequency such as 10-20 Hz would be suitable for rejecting false positives, but not very suitable for recognizing true positives. Two lower cut-off frequencies were therefore chosen to generate a prototype that would be useable, and also to illustrate that a trade-off between having a high accuracy in recognizing true positives and a high rejection rate of false positives might be necessary.

The prototype was designed with a visual feedback through LED activation on a successful input recognition. This was chosen in order to simplifying the process of learning to perform accurate tapping motions for the subjects. The used microcontroller was chosen due to its size and capability for data logging, a feature that was used during development and testing of the prototype, but not during the conducted study.

5.5 Study design

The study was designed with three objectives in mind:

1) It should provide a preliminary investigation into the performance of the used accelerometer and using accelerometers in general for generating user input, using tapping on and turning the prototype as user input patterns.

2) It should investigate the experience of the user using an accelerometer UI.

3) It should compare how well users were able to use the tapping function with their non-preferred working hand.

The first objective was deemed to be fulfilled by the two first parts of the test, where the tapping test was done with two different cut-off frequencies for the used filter. This showed that the performance of the accelerometer is heavily dependent on the processing done on the accelerometer data. The second objective was deemed to be satisfied by the questions asked regarding the subjects experience on using the tapping and turning functions. The third objective was deemed investigated by performing the test on both the right and left side of the head, and recording which hand was the subjects preferred working hand.

However, a few weaknesses in the study was noted both before and during conduction of the study. Even though the subjects were given 2 minutes to familiarize themselves with the prototype and its functions, the learning rate seemed to still impact the result of the study. It seems unlikely that users would be more proficient in tapping with their non-preferred hand compared to tapping with their preferred working hand. Still the results show that the success rate was higher when tapping on the left side of the head, even though only one subject preferred working with their left hand. The logical conclusion to this fact is that the learning rate enabled subjects to perform better in the third part of the study. This should have been avoided or mitigated by randomizing the order in which the different parts of the study was performed for each subject.

This study was performed on employees at Cochlear Bone Anchored Solution AB, none of which were an actual user of a Baha 5, or any hearing device. This is a source for questioning the credibility of the study, unless a thorough comparison of the differences between performing the study on users and on non-users of the Baha 5 or another hearing device is performed.

All subjects were also between the ages of 25 and 53, which is a far narrower span than the ages of patients that use hearing devices. Since age can have an impact on motor skill, the limited age span of the subjects in this study could impact the results.

Another issue with the study was that when performing the tapping, subjects were not told to perform another action in between each tapping on the prototype, leading to each subject placing their hand close to the prototype permanently for each test round of taps. This lead to that any issues related to locating the position of the prototype on the side of the head were not investigated, and that the taps on the prototype were most likely not as similar to a real world situation as they would have been if the subjects would have been forced to perform some other action in between each tap.

5.6 Future work

The used filter is one of the largest weaknesses of the current prototype. While it has its strengths in being computationally cheap and simple to implement, it is unable to distinguish user generated taps from high-intensity noise, such as heavy walking in stairs. Experiments were performed outside of the study with higher order high-pass filters, up to fifth order filters, with various cut-off frequencies ranging from close to 0 Hz up to 50 Hz, all with either similar or poorer results than the used first order filter. However, other filters than IIR high pass filters were not experimented with, and more advanced filters could generate improved results, and should be a target for further study.

Additional areas worth investigating is the optimal placement of the accelerometer relative to the tapping position, as well as the performance of other accelerometers compared to the one used in this study.

Finally, additional studies should be performed where actual patients are included, since the method of attaching the hearing device to the patient might impact the performance of the accelerometer. Patients with a wider age range should also be included, to study the impact of decreased motor skill on the ability to use a accelerometer UI. Studies with different activities should also be performed, featuring activities such as running, lying down and rising up.

6
Conclusion

The results indicate that it can be feasible to generate user input with an accelerometer, given that it is possible to increase the accuracy of the pattern recognition and rejection rate of false positives. It also indicates that:

- given an acceptable performance with regards to low amounts of false positives and high accuracy in recognizing input patterns, users would prefer using an accelerometer UI to generate input compared to a push button UI;
- users can use the accelerometer UI to generate input even when the hearing device is located on the side of the head of their non-preferred working hand without any major loss in performance; and
- that the main issues in using this technology concern identifying an accelerometer with high enough precision, as well as achieving acceptable levels of recognized input patterns and false positives.

Furthermore, this report has indicated numerous areas for continued research towards a commercial implementation of an accelerometer UI.

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