DETECTION AND CLASSIFICATION OF THE SOUNDS PRODUCED BY ARTIFICIAL HUMAN HIP IMPLANTS

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Declaration

I declare that this dissertation is my own, unaided work, other than where specifically acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

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Abstract

Total hip replacement has become a common procedure in the treatment of hip disorders. In doing so, the bony components of the hip are replaced with artificial inserts. Regular follow-up is required for all joint replacements to anticipate complications. However, in recent times sounds emanating from the implants have been identified and there is an interest in their causes and implications. It is the latter of these concerns that is the focus of this document.

Sounds were recorded from the hip implants of participants while they performed a number of specified movements. This was achieved using an electronic stethoscope.

Spectrograms were used to identify individual sounds in the complete recordings. In order to filter out the background noise from the recordings, a 5th order Savitzky-Golay filter with a window width of 21 points was implemented. The effectiveness of this filter was confirmed by cross-correlating the original and filtered signals to ensure preservation of low frequencies.

The discrete wavelet transformation was used in order to distinguish between the different sounds. The symlet8 wavelet was used and the signals were decomposed into 10 detail levels. Using this method, 3 different sound classes were identified based on the different wavelet levels. These classes were further characterised by determining the skewness and kurtosis of the Welch power spectra. Upon listening to the sounds, it was found that the three classes also appeared audibly different.

A sound detection and classification procedure, based on the wavelet characteristics and the classes defined, was developed and tested. It allowed individual hip implant sounds to be characterised in previously unseen and unanalysed recordings. These sounds were analysed and classified into one of the 3 main sound classes.

A number of patient and implant factors were also considered in trying to identify whether any condition might predispose an individual implant to produce sounds.

These include body mass index (BMI), implant age, implant angle, movement performed and bearing surface combination. The ceramic-on-metal implants, and implants in participants with overweight BMI scores produced the most sounds. Despite this, no consistent links between these factors and the sounds produced could be identified.

The occurrences of the 3 different sounds classes within the different patient factor groups was also investigated. This was done to determine whether or not the pattern of occurrence could be used to determine which of the patient factor groups an unknown recording belonged to. This, by extension, might reveal some information about the implant producing the sounds. However, the occurrence patterns were so similar in many patient factor groups studied that this technique was considered unfeasible. One exception was the different bearing surface combinations, each of which exhibited a different occurrence pattern. Therefore, the occurrence of certain wavelet characteristics may be used to suggest which of the bearing surface combinations a hip implant contains. Another exception was the overweight BMI group, which had a distinct sound class occurrence pattern, and therefore wavelet characteristic pattern, from the underweight and obese BMI groups.

This research supports aspects of previous work done on the topic, and introduces a new methodology to acquire hip implant sound data. In addition, new classes of implant sounds are defined. Discrete wavelet decomposition was shown to be an effective signal analysis tool for this problem. Much work remains to be done on hip implant sounds and these findings add to the growing collection of knowledge on the subject.

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Contents

Chapter 1

Introduction

Since their invention in 1964, hip implants have improved the lives of thousands of people. Over the subsequent years much research has been done and effort expended to optimise their performance. Some of the topics include the proper selection of manufacturing materials and ensuring they can withstand the forces to which a hip is subjected on a daily basis.

Routine monitoring of hip replacement patients is essential and involves functional, clinical and radiographic check-ups to ensure there is no infection and that the hip implant remains in its correct position. There are a number of issues that are of interest to the orthopaedic community. These include the wear patterns on the implant surfaces, the effects of the metal ions released by the implant on the human body and the sounds that the implants produce. It is this last issue that is the subject of this document.

Sounds are occasionally reported to emanate from the implants. These sounds have varying levels of severity as well as random occurrence patterns. However, it is possible that there may be some information contained in the sounds and that this information could relate to the state of the implant.

1.1 Statement of the Problem

In order to identify what information may be contained in the sounds produced by hip implants a new study was proposed. This study was aimed at increasing the current pool of knowledge regarding the occurrence of sounds without looking at the microscopic causes of the sounds themselves. In order to achieve this, a number of objectives were identified.

A method of reliably recording the sounds will need to be identified. To do this, a number of constraints were placed on the selection of the apparatus. It was preferable to use a pre-existing technology that was readily available to orthopaedic specialists and easy to incorporate into the current follow-up procedure. It should also be non-invasive to ensure minimal discomfort for the patients.

In order to gain information from the recorded sounds, signal analysis techniques would need to be employed. This research will identify the techniques to be used and thereby determine any distinguishing patterns or characteristics of the sounds.

These characteristics will be further used for the detection of individual sounds in previously unseen and unanalysed recordings. These sounds will then be classified according to their characteristics.

A number of patient factors have previously been considered to be possible causes of the sounds. As such, correlations between the signal characteristics of the sounds, the occurrences of the sounds and the patient factors will be investigated. The correlations to be studied are listed below:

- sound occurrence and body mass index
- sound occurrence and implant angle
- sound occurrence and implant age
- sound occurrence and bearing surface combination
- sound occurrence and movement performed

It would also be of interest to know whether the different bearing surface combinations used produced different sounds, and which one produced the most sounds.

1.2 Document Structure

This document provides details of the study conducted and the details obtained. It begins with a detailed discussion of the history and current standing of hip implant sounds research. This is followed by the decisions taken to implement the study and collection of the necessary data. The data is analysed and the chosen analysis methods are described The results obtained are presented and their implications are discussed. Finally the study and its findings are placed into context within the existing body of knowledge.

Chapter 2

A Brief Overview of Total Hip Replacement

The human body is capable of a vast array of movements and postures. This is made possible by the body's intricate musculoskeletal system. While the neurological system acts as the originator and controller of the body's movements, it is the various parts of the musculoskeletal system that are the effectors of human motion. This motion occurs at the joints in the systems, each of which is highly specialised as to its purpose.

Of particular interest to this discussion is the human hip joint. In this chapter, a description of its structure and functional adaptations will be provided. A discussion of the problems the hip joint experiences will be presented, as will the development and use of hip implants. It will conclude with the identification of the focus of this research.

2.1 The Structure of the Hip Joint

The human hip joint serves as the point of attachment between the body and the lower limb. It is a synovial ball-and-socket joint, so called because of the connection between the two articulating surfaces of the joint. The surfaces in question are the head of the femur and the cup-shaped socket of the pelvic bone, the acetabulum. The head of the femur sits almost entirely inside the acetabulum and is held in place by the muscles and ligaments of the hip joint. This arrangement is shown in Figure 2.1. It allows for a suitably wide range of motion without compromising joint stability. It also allows for the forces generated by the weight of the upper body

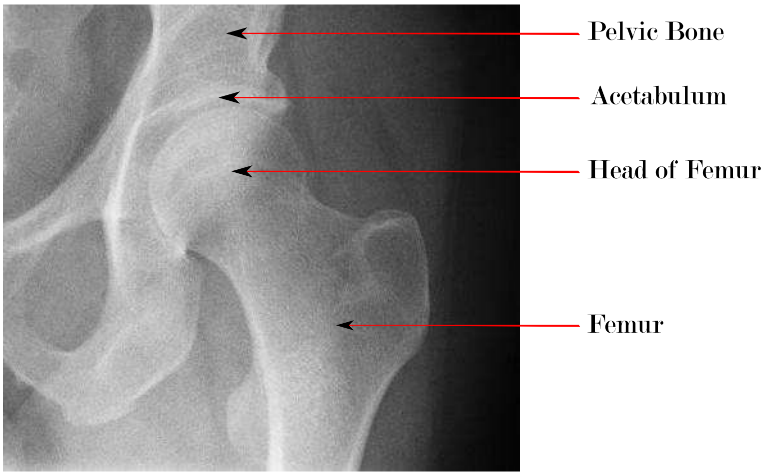

Figure 2.1: An x-ray of a healthy human hip joint [3]

to be transferred to the lower limbs and assists the maintenance of balance during movement [1, 2].

2.2 Hip Injuries

Despite the adaptations of the hip joint to its function, it is still prone to injury, disease and aging. As the body ages, the neck of the femur becomes osteoporotic, making it prone to fracture. Other possibilities include general wear-and-tear on the joint due to daily activities, avascular necrosis and osteoarthritis.

Various treatments are available for these ailments. However in extreme cases, it may be necessary to replace the joint completely. This is a surgical procedure involving the replacement of all the bony components of the hip joint.

2.3 Total Hip Replacement

The hip joint is replaced in a surgical procedure known as total hip replacement (THR). When THR is performed, the head of the femur is removed, as is the lining of the acetabulum. A hole is drilled down the shaft of the femur and a femoral component is fitted into it. A head is then fitted onto the top of the femoral component. A metallic cup or shell is fitted into the acetabulum and an insert or liner is fitted into the shell. The structure of the implants is shown in Figure 2.2.

Today THR has become commonplace in many countries in the world and it enjoys a high success rate.

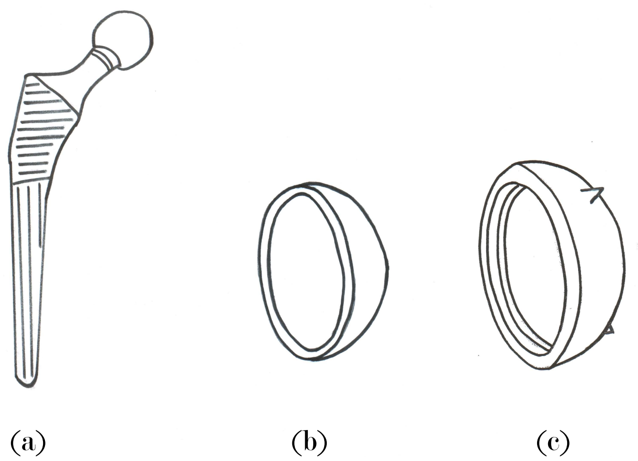

Figure 2.2: Hip implant (a) Femoral component (b) Liner (c) Acetabular component/shell [drawn by author]

The stem of the femoral component is typically made of either titanium or stainless steel. The femoral head component is made of a CoCr alloy or ceramics. The acetabular insert is made of a metallic liner or an ultra-high molecular weight polyethylene (UHMWPE) liner or a ceramic liner. These particular materials are used because they are biocompatible, they are resistant to wear and corrosion and they are structually able to cope with the large forces placed on them [4, 5]. The materials are typically used in various combinations, resulting in the four most common bearing surface combinations, which are listed below:

- ceramic femoral head with ceramic liner (CoC)
- ceramic femoral head with polyethylene liner (CoP)
- ceramic femoral head with metal liner (CoM)
- metal femoral head with metal liner (MoM)

A number of possibile problems can occur with the implants. These are [6, 7]:

- bearing surface wear

- loosening of the implant
- infection
- dislocation
- periprosthetic fracture

Loosening is the most commonly occuring complication and can lead to damage to the surrounding bone. [7]. Another cause for concern is the release of wear particles from the materials used in the bearing surfaces. Studies into this are currently underway [8]. The materials chosen are not believed to have any serious effect on the body but this has yet to be confirmed or disproved. There is also a small chance of patients experiencing allergic reactions or sensitivity to the materials used.

2.4 Sounds From Implants

Today, THR has become a routine procedure, improving the lives of thousands of people worldwide. However, in recent times a new issue has garnered attention, namely that of the sounds produced by the implants. In previous studies, up to 20% of people who have had implants have reported sounds [9–12]. However, there are conflicting opinions on whether the sounds are a cause for concern or not [13, 14]. It is not yet clear if the sounds may be an indicator of the condition of the implant.

2.4.1 Causes of the Sounds

There has been much research into the causes of the reported sounds. While the sound itself may not be problematic, it is possible that it could be an indication of problems with the implant.

The impingement of the femoral neck on the acetabular component has been cited as a major cause. This can be aggravated by improper positioning of the implant [15–17]. The presence of third body particles between the two articulating surfaces and a lack of lubrication have also been put forward as possiblilities [9,18]. A person's weight, general health and activity level may also have an effect. Implant age may also be a factor, since no sounds are reported from new implants but increased ultrasonic activity has been reported in older implants [17].

People who report sounds from their implants often complain of it while performing specific physical activities. This may be a regular occurance or it may not be. In this case it may not necessarily be a cause for concern, although it could be a source of some embarrassment for the person.

The choice of implant has also been considered as a factor [19,20]. It is possible that the sounds are related to the type of bearing surface combination used in the patient. At present, four different combinations of bearing surfaces are used. These are ceramic heads with ceramic liners (CoC), metallic heads with metallic liners (MoM), ceramic heads with metallic liners (CoM) and ceramic heads with polyethylene liners (CoP). To date, only sounds produced by the hard bearing surface combinations, namely CoC and MoM, have been studied in detail [12].

2.4.2 Sounds Characterisation to Date

There is currently an interest in characterising the sounds reported by patients. This may allow orthopaedic specialists to determine the state of the implant based on the sounds they produce. Another possibility is that patterns exist in the sounds and that there may also be inaudible sounds. For example, it is possible that the sounds generated when a patient sits down can be repeated and are similar from patient to patient.

Many different characterisation methods have been tried and they have all produced different results. One method is the determination of the frequencies that can be found in the recordings [21–23]. There has also been some work on correlating the sounds with the movement of the joint [21, 24].

Vibration and resonance of the implant components have also been studied in the quest to better understand and characterise the sounds [25, 26]. However, these studies have involved forced vibration of the implant.

In recognizing these findings, it is possible that the sounds recorded from hip implants may be able to convey some information about the functioning of the implant.

2.5 Conclusion

The human hip joint is a strong and stable structure that is well adapted to its function. However it is not impervious to damage. In severe cases the hip joint may be replaced with an artificial implant. This procedure has enjoyed much success. However, in recent times, there have been reports of implants producing sounds. There is ongoing research into the causes of these sounds. Very little is known about the sounds themselves and whether or not they should be a cause for concern. In order to rectify this, the sounds must be recorded and analysed to identify their characteristics and to determine whether the sounds may convey information regarding the state of the implants.

Chapter 3

Overview of Experimental Procedure

In order to identify the characteristics of the sounds, it was necessary to first collect the data. This was done by recording sounds from a collection of patients with hip implants. Since four different bearing surface combinations were studied, sounds were recorded from individuals from all four groups. The patients were taken from an existing study "'Randomised study of four bearing surface combinations in Total Hip Replacement"' [27].

3.1 Experimental Method

Sounds produced by hip implants often prove difficult to record. Many patients report only occasional sounds that do not occur regularly and are not always reproducible. There may also be sounds produced by the implant that the patient does not hear. As a result, it is necessary to employ a recording method that is able to detect all these sounds and that will not prevent the patient from performing everyday movements.

To this end an electronic stethoscope was used. Specifically, the ds32a Stethoscope supplied by Thinklabs Medical was employed. The sounds were recorded onto an Apple iPod Nano using an Xtreme MacMini Voice Recorder. This method was recommended by Thinklabs [28]. The equipment used is shown in Figure 3.1.

To record participants' hip sounds, the probe of the stethoscope was held onto their hip using a self-adhesive bandage. The participants were requested to perform various physical movements. These included walking, climbing stairs and sitting in a chair. These movements were chosen because they are common movements that an individual will perform many times in a single day, and it is these movements that are likely to have the greatest effect on the wear and tear on a hip implant. The patients were also video recorded while they performed the various physical movements. This was done to allow for correlation between the recorded sounds and the gait cycle.

All participents were also asked to complete a questionnaire. The purpose was to determine whether or not the patient had noticed any sounds from their implant and for how long the sounds had occured. This information was used in the correlation process.

(a) **(b)**

Figure 3.1: Equipment used in data capture (a) Thinklabs Medical ds32a Electronic Stethoscope (b) Apple iPod Nano

3.2 Ethical Considerations

Since the data used for the analysis was recorded from patients, it was necessary to obtain ethical approval. An application was submitted to the University of the Witwatersrand Human Research Ethics Committee. This was approved unconditionally. Patient information sheets, questionnaires and consent forms were drafed in accordance with the committee guidelines. The patients were requested to sign a consent form before taking part in the study. Confidentiality was assured and all recorded data was depersonalized. That ensured that the names of patients do not appear anywhere in the study.

The data for each participant was collected and analysed in a blinded manner. The information regarding each participant's implant bearing surface combination was not revealed until the very end of the analysis process. This was done to prevent any biasing of opinions or expectations of the results.

3.3 Methodology

The idea of joint auscultation is not new. It has been tested in the past and has shown some degree of success, as described in [29–31]. It has been shown that a distinction can be made between healthy knees and arthritic knees based on the sounds they produce [32]. However, the method fell out of favour. If it could once again be shown to be effective, then it is possible it may be adopted as a quick and easy diagnostic procedure when checking the performance of a hip implant.

A stethoscope is a device that all doctors own and it was therefore a logical choice when deciding what equipment to use in the evaluation of this process as a diagnostic procedure. An electronic stethoscope was used since it allowed the sounds to be recorded and saved for further analysis. It also had the added advantage of being lightweight and portable. This meant that the participants were able to move around freely without being hindered by long cables or heavy recording equipment.

The probe of the stethoscope was strapped onto the hips of the patients using a self-adhesive bandage. This was used because it was portable, lightweight, easy to apply and remove and required no pins to hold it in place. This removed all possibility of injury to the patient.

In order to identifiy the approximate position of the hip implant during the movements, the participants were video recoded while they moved. This is a standard procedure used in gait analysis [33].

3.3.1 Advantages of this method

The stethoscope performed well and all sounds were reliably recorded, allowing signal analysis to be performed. The general use of the stethoscope was quick, easy and uncomplicated. The recorder worked as expected and was not difficult or time-consuming to administer. It was also convenient for the participants. Since this was one of the overall objectives it can be stated that the method was successful for this application.

Further analysis of the recordings revealed that minute sounds were in fact detected by the stethoscope. It is noted that sounds were often identified in the recordings when the participant stated that there were no sounds. This indicates that the stethoscope was successful in detecting sounds that are inaudible to the human ear.

The use of a self-adhesive bandage to hold the probe on was also successful. Participants experienced unobstructed movement and were able to move around freely. It was easy to apply and remove, thus putting the participant through a minimum amount of discomfort.

3.3.2 Problems Encountered

The primary problem encountered during this study was the unreliability of the sounds themselves. Even if a participant reported that they heard sounds there was no guarantee that they could reproduce the sounds on demand.

Stethoscopes work on the basis of a doctor knowing what it is he or she is trying to hear. Heart and lung sounds are all well documented and there is little variability from person to person. Even pathologies are well known. The same is not true of hip implant sounds and joint sounds in general. The sounds that were recorded in this study were not regular enough to definitively say that they can or cannot be used for diagnosis purposes.

Another issue is the stethoscopes sensitivity to all background noise. Stethoscopes are very sensitive to the pressure placed on the probe by the person using it. Different pressures change the frequency response of the stethoscope, which makes them sensitive to different sounds [34,35]. This allows for lung sounds to be distinguished from heart sounds since the two are known to contain different frequency components [35]. In the case of joint auscultation it is difficult to ensure that the pressure is constant during the movement of the participant. The presence of the bandage over the bell end of the probe also caused soft scratching sounds to be heard, which were recorded along with the hip sounds, thus introducing interference into the signal. This noise was very difficult to quantify. The fact that the stethoscope was electronic also made it susceptible to electronic noise caused by cell phones and other electronic devices in the area.

The frequency response of the stethoscope is highly variable due to the response of the stethoscope being dependent on the pressure with which the probe is applied and the material to which the probe is held. It is also dependent upon the surface of the stethoscope probe that is being used; that is the bell or the diaphragm. Each of these are sensitive to different frequency bands. The impedance mismatch between the skin and the air causes reflections of the sound vibrations, which results in decreased energy being transmitted across the interface [34,35]. However, due to the variation in impedances between individuals, this is very difficult to quantify.

While the recorded signals did contain useful information, much analysis was needed to extract it. This makes this method impractical as a realtime diagnostic tool since it would require time and digital processing. If this analysis process could be automated, this problem would be reduced.

The videos of the partipants were not accurate enough to identify any patterns in the movements of the implant. The partipants often walked out of range of the camera. Each movement was only performed for three or four gait cycles, which was not very long. Therefore correlations could not be reliably drawn.

3.3.3 Evaluation of Effectiveness

The experiment was designed to record the sounds produced during movement and to be portable and non-restricting. It was successful on both these counts. When compared to other recording methods described in the literature, it may seem rather simplistic [21,23]. However it is important to note that this simple method compares well with more purpose built equipment. This shows that the method is technically possible, although the raw data obtained may not be immediately useable.

It is also worth noting the percentage of participants who reported hearing sounds before they performed the movements. Of the 92 implants surveyed, 19 were reported to produce sounds. This is 20.65 % of the total sample. This is consistent with ranges previously reported: 10% - 22% [9–12,22]. In other studies participants were specifically chosen based on a set of predefined criteria. In this experiment the participants were randomly chosen. They attended their routine follow-up appointments in a random order over a year. This shows that the two scenarios have produced similar results and that sounds being emitted from hip implants is perhaps a completely random phenomenon.

The esperiment could be expanded in the following ways:

- Inclusion of Natural Hips: this study was limited to artificial hip implants. In order to compare the sounds measured with any sounds produced by natural bone hips, a control group could be included.
- Sound movement localisation: participants could be made to move within a fixed area and perform the same movements many more times, for example walking on a treadmill. This could be coupled with video recordings to allow the sound to be identified within the gait cycle.

3.4 Conclusion

In this chapter, the experiment performed to collect the sound data from the hip implants was described. The equipment used was described and the reasoning for the choices made were given. It was shown to be effective, since it recorded sounds from the implants, however it was also impractical, due to the significant extent of analysis still required. Recommendations for future experimentation were also given.

Chapter 4

Data Analysis

Once the sounds had been recorded they were subjected to signal analysis. This was done so as to identify the underlying characteristics of the sounds. A number of techniques were implemented and they are discussed in detail in the subsequent sections.

Various objectives were achieved as a result of the analysis. Individual sounds were identified within the total recordings and, based on their specific characteristics, were divided into a number of classes. The occurances of the different classes were used to test the original correlation conditions. In so doing the usefulness of the sounds in determining the state of the hip implant could be evaluated.

4.1 Signal Identification

The recordings were first analysed by ear to determine whether any sounds could be detected without assistance or amplification. This was rarely the case and the recordings had to be greatly amplified before any audible sounds could be detected. It was noted that different levels of sounds were detected in different recordings. This was the case regardless of whether or not the participant reported hearing a sound themselves.

Spectrogram plots were used to identify when individual sounds occured during the total recordings. A brief discussion of spectrograms and their application in this instance are given below.

4.1.1 Spectrogram Theory

A spectrogram is a graphical representation of the time-frequency relationship of a signal. The frequencies present at each instant in time are shown. In this manner, variations, similarities and patterns in the spectral characteristics of a signal can be identified [36].

Spectrograms are generated by splitting the total signal up into short segments using a window function and then taking the Fourier transform of each of the individual segments. In so doing, the frequency components of each of the time segments are calculated. The transformed segments are then cascaded together to produce a 3-dimensional plot. Time is represented on one axis, frequency on the second axis, and the magnitude of the frequency is shown by the intensity or colour of the graph [36]. Spectrograms are used extensively in voice recognition, testing of filters and phonetics [36].

4.1.2 Spectrograms in hip sound identification

In this study spectrograms were used to identify sounds in the total recordings made while the participants performed the set movements. They were used in conjunction with auditory identification to confirm or reject sounds, and to identify noise. Electronic noise in particular was detected in the spectrograms by its characteristic spectral patterns, as shown in Figure 4.1. If a spike was seen but no sound was heard, it was identified as noise and not included in further analysis. If a signal was heard and corresponded with a spike in the spectrogram plot, that section of the recording was cut and saved as an individual sound. This was consistant with the study's requirement to detect the sounds produced by implants. The details of participant number and time were noted, to be used in later correlations.

4.2 Noise Removal and Filtering

The recordings captured contained large quantities of noise. This required the removal of the noise through filtering. No prior knowledge of the frequencies contained in the signals existed and, although this could be determined by using a fast Foutier transform, the contribution of each frequency to the actual hip implant sound could not be determined. Without this knowledge, it was not desirable to

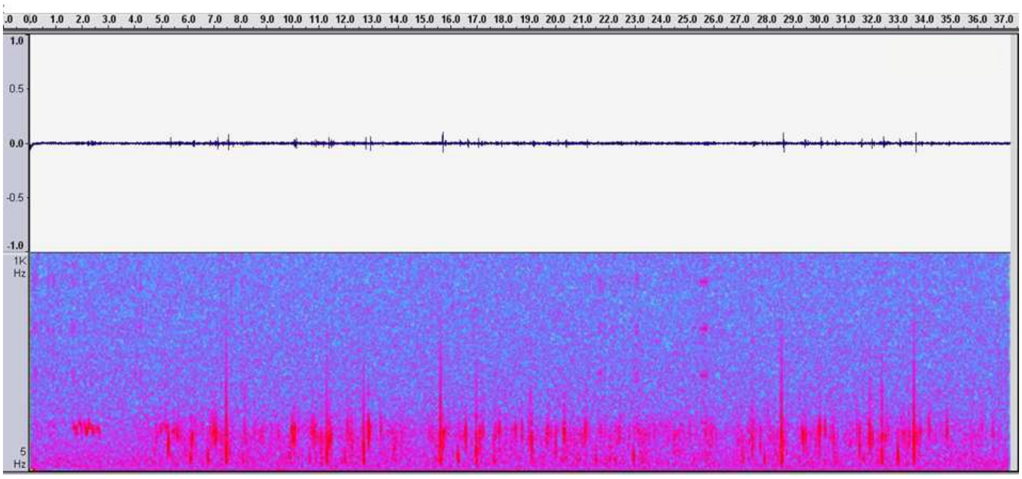

Figure 4.1: Spectrogram plot of a hip recording

simply choose a frequency and remove everything abover or below that for fear of excluding signal information. Therefore a curvefitting Savitzky-Golay filter was used, which allows for effective filtering in the time domain.

4.2.1 Savitzky-Golay Filter Theory

The purpose of filtering is to remove unwanted extraneous data from a signal without degrading the underlying important information. Curvefitting is the process of drawing through a set of data points a line which best fits them. In so doing, extra information can be removed and thus filtered out. In implementing a Savitzky-Golay filter the method of least squares is used, in which a polynomial curve is fitted to the data points [37].The general equation for this filter is given equation 4.1 below [38]:

$$g_i = \sum_{n=n_L}^{n_R} c_n f_{n+i} \tag{4.1}$$

where n_L to n_R define the width of a window over which a curve is fitted and c_n defines the Savitzky-Golay co-efficients for the filter.

A Savitzky-Golay filter is a type of low-pass finite impulse response (FIR) filter. It has the advantage of being efficient at preserving specific features of data, such as maxima, minima and feature width. It also allows for preservation of high frequencies, depending on the selection of polynomial, that are normally discarded by low-pass filters.

In order to achieve the best fit a polynomial order and window size must be defined. A window is the number of points used to define the polynomial over a given subset of the total dataset. If the window is too small the noise will be used in the curvefitting and will not be excluded properly. If the window is too large the curve will not fit the data accurately enough. The window is moved along the total dataset to obtain a fit for the underlying data [38, 39].

The choice of polynomial order is also important. If the order is too high the curve will not reject the noise. If the order is too low feature heights and widths will not be preserved [37].

Although the exact frequency contents of the signals were not known, only low frequencies are of interest [21, 22]. Therefore the filtered signal should still retain these in order for the sound to be preserved. To test this, the fast Fourier transforms (FFTs) of the original and filtered signals were cross-correlated. The filter that produced the greatest range of preserved low frequencies, while removing high frequencies, was chosen as the most effective. This was achieved using a window width of 21 points and a 5th order polynomial.

4.2.2 Filtering Results

The Savitzky-Golay filter is inherently a low-pass filter. This means that it will allow low frequencies to pass through unhindered but will reject high frequencies. Since the recorded sounds existed in the audible, low-end of the frequency range, this was deemed acceptable. The filters were successful in removing the high frequency noise and this made the sounds much easier to hear. It also made the sound features, such as signal spikes, easier to identify in the overall recording. A plot of one of the sounds, before and after filtering is shown in Figure 4.2.

4.3 Sound Characterisation and Classification

Since specific sounds had now been identifed, they could be characterised and defined. This was necessary to accurately distinguish between the sounds to identify any similarities and differences.

A number of techniques exist for this purpose. In this instance the discrete wavelet transform was selected, as it allowed the different frequencies contained within the

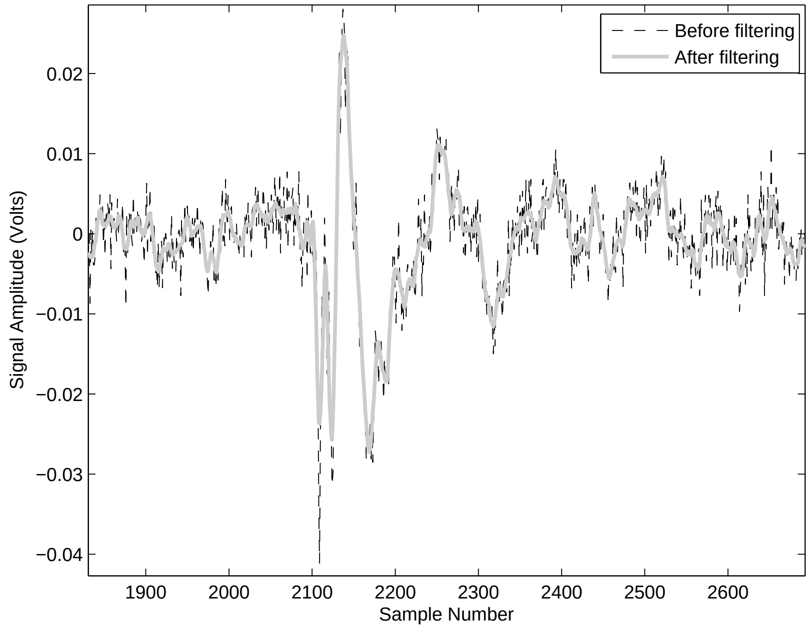

Figure 4.2: Sound before and after filtering

original sound segment to be clearly identified. These differnt frequencies were then used to define the classes and sounds.

4.3.1 Discrete Wavelet Decomposition

The discrete wavelet transorm involves the correlation of the original signal with a Gaussian wavelet. The resulting co-efficient is an indication of the degree of similarity between the two signals. The scale, or width, and amplitude of the wavelet are then altered and the correlation is repeated, thus resulting in a new set of correlation coefficients [40, 41].

The scale of the wavelet can be related to the frequency of the wavelet. That is, each different value of scale provides information about a different frequency band. The higher the co-efficient values, the more prominent the specific frequency band appears in the original signal [42].

The scale of the original wavelet basis function is altered by a factor of 2 each time. This results in subsampling by 2. As such, this form of signal analysis has many applications, including EEG analysis and subband coding.

Parameter Selection

Each level of detail highlights various frequencies that are present in the signal. These signals were sampled at 22kHz [34] and therefore contain frequencies up to 11kHz, according to Nyquist's theorem [43]. As such, the first detail level consists of frequencies from 5.5kHz to 11kHz. The subsequent levels each contain the frequencies that are a factor of two smaller than the previous level. This is the result of subsampling a factor of by 2, which is how the discrete wavelet transform is implemented [42].

Ten levels of frequency detail were used for this analysis. This was because these levels provided adequate coverage of low frequencies without becoming computationally expensive. The frequencies contained in each detail level are given in Table 4.1 below.

Table 4.1: Levels and corresponding frequencies

Level	Frequencies
1	5.5kHz - 11kHz
2	2.75kHz - 5.5kHz
3	1.375kHz - 2.75kHz
4	688Hz - 1.375kHz
5	344Hz - 688Hz
6	172Hz - 344Hz
7	86Hz - 172Hz
8	43Hz - 86Hz
9	21Hz - 43Hz
10	11Hz - 21Hz

The signals extracted from the recordings are transient and aperiodic. As such, they are best analysed using asymmetrical wavelet basis functions [44]. Therefore, the Daubechies, symlet and coiflet wavelet families were tested to find the one most suited to this analysis. The signals were decomposed into their wavelet levels and these were then used to reconstruct the original signal. The basis function that produced the lowest error when its reconstructed signal was compared to the original signal was used. This was the symlet8 wavelet.

4.3.2 Feature Identification and Classification

The wavelet decomposition levels were used to identify which frequencies are dominant in each signal, and to spot any trends. This was done by examining the amplitudes of the coefficients and ordering the levels in descending order of dominance. A number of conclusions were derived:

- very high frequencies (level 1 and 2) and very low frequencies (levle 9 and 10) are consistantly least dominant
- level 4 frequencies (688Hz to 1.375kHz) feature prominantly in almost all sounds
- some sounds have lower frequencies being more dominant (ie levle 6,7,8) while others have higher frequencies being more dominant (ie levle 3,4,5)
- this analysis may be taken a step further by taking FFTs of each individual level to determine which frequencies are dominant within the specific range. This also serves to confirm the frequencies contained in each band

Since the sounds had now been analysed, and a number of frequency differences were noted, it was considered possible that the sounds may appear different to the human ear. In order to determine this, each group of sounds was listened to to see if they sounded the same or similar. This was the case in 83% of sounds.

By taking note of the above observations the sounds may be divided into three categories. These are defined and described below and signal plots may be found in Appendix A:

- Primary Clicks - these are defined as impulse-like metallic sounds. They contain dominant frequencies in the ranges of 400Hz to 500Hz (level 5), 1600Hz to 1800Hz (level 3) and 800Hz to 1200Hz (level 4).
- Primary Clunks - these are impulse-like hollow sounds. These are also often the loudest and easiest to identify. They contain dominant frequencies in the ranges of 800Hz to 1000Hz (level 4), 400Hz (level 5) and 80Hz to 100Hz (level 7).
- Primary Knocks - these sounds are impulse-like and muffled. They contain dominant frequencies in the ranges of 300Hz to 400Hz (level 5), 100Hz to 150Hz (level 7) and 200Hz to 250Hz (level 6).

In addition to these, two more categories were identified. These contain the sounds that are less definitive in their caracteristics:

- Secondary Grating - these are extended versions of the other three sounds.
- Secondary Compound sounds - these are made up of one or more of the above mentioned sounds occuring immediately after one another.

This classification allows the sounds to be classed and quantified when considering the number of sounds that are identified in each recording.

It is noted that the above conclusions are general trends and they are neither exact nor fixed. While the trends are valid for a large percentage of the sounds recorded it is extremely rare to observe the same frequency dominance pattern in consecutive sounds. This would make automated recognition difficult.

4.3.3 Power Spectral Density

The power contained in the signals is also worth analysing. In order to do this, a Welch power density spectrum was used [45, 46]. This method calculates the power density spectrum of a signal multiple times and then averages the separate spectra. In doing so, the power due to random noise is removed, thus creating a smooth curve that is easy and efficient to analyse [46]. The different graphs are shown in Figure 4.3 below.

In analysing the power spectra resulting from each of the defined sound classes, it is noted that the different classes have distinctly different power spectral density plots. In order to better quantify these differences, the skewness and kurtosis of each class was calculated [47].

Skewness is a measure of the asymmetry of a dataset. It gives an indication of the level of variation around the mean value of the dataset. If the skewness is positive, then the data is distributed to the left of the mean value and vice versa [48].

Kurtosis is a measure of the how close to the mean value of the dataset the peak value lies. In so doing, an indication of how prone a dataset may be to outliers is given. The nominal value, that is, the kurtosis of a normal distribution, is 3 [48].

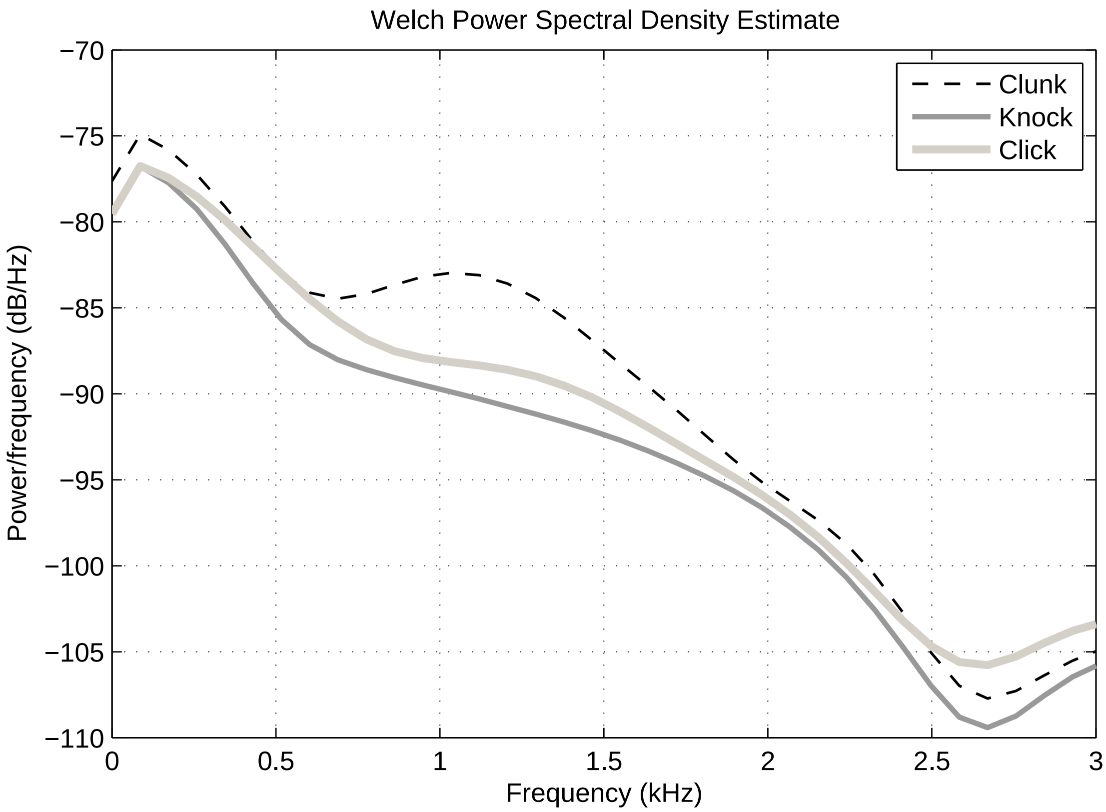

Figure 4.3: Power spectral densities of the different sound classes

Since two distinct curves can be identified on the graphs of each class, they were divided up as shown in Figure 4.4 below. The skewness and kurtosis values of each area were then calculated. These values are given in Table 4.2. Although all the values are close, they are consistent across the entire range of samples. It can therefore be stated that skewness and kurtosis of the power density spectra from each class may be a possible tool for distinguishing between the different sound classes.

Table 4.2: Skewness and kurtosis of the recorded signals

	Clunk	Click	Knock
Skewness 1	0.6848	0.6191	0.6889
Skewness 2	0.6775	0.4489	0.2703
Kurtosis 1	2.1705	2.0844	2.1378
Kurtosis 2	2.0806	1.9399	1.6674

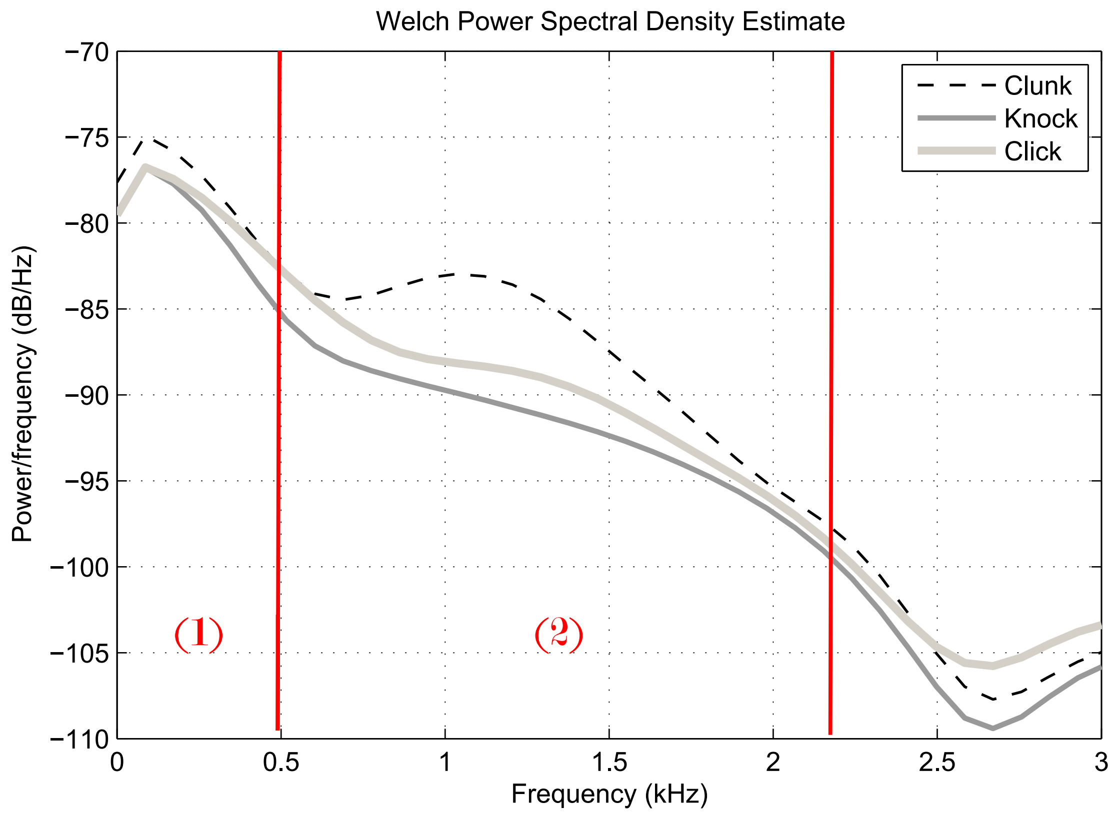

Figure 4.4: Power spectral densities divided into two areas

4.4 Automated Signal Analysis

It was investigated whether the characteristics identified above could be used to detect and classify sounds in previously unanalysed recordings. This would go some way in determining the feasibility of using these properties in the further development of a fully automated analysis system.

4.4.1 Analysis Procedure

The procedure for the signal analysis is described below:

1. Detect the sounds in the total recording using peak detection methods. The total number of peaks identified is noted.

2. Remove the sound using a window.

3. Filter the sound using the S-G filter, defined in Section 4.2.1, to remove noise.

4. Perform the discrete wavelet transform, as discussed in Section 4.3.1. The resulting 10 frequency levels must then be compared with those defined as the characteristics of the classes. This is done by studying the values of the wavelet coefficients for each wavelet decomposition level. The levels are then arranged in order of wavelet coefficients. This is because each of the classes had different wavelet levels that were dominant and this is indicated by the wavelet co-efficient value. Depending on the order of the decomposition level, the signal is then classified.

5. The FFT of the three most dominant levels of the wavelet decomposition are then calculated and these are cross-correlated with those from the original class definitions. This is done to confirm the original classification.

6. Check Welch power density spectrum. The PSD is divided into the two regions identified above and the skewness and kurtosis are calculated. The values are then compared to those for the defined classes, as described above, and this is used to confirm the classification of the sounds.

It is noted that a degree of tolerance must be allowed to account for individual variability. These are given below as:

- A correlation co-efficient of 0.8 and above indicates a good match. This was determined empirically.
- A tolerance of 0.05 is allowed in the calculations of skewness and kurtosis. This is because the values for different classes, although consistent, are very close and therefore a small difference could mean the difference between the two classes. This is also why the DWT is used as the primary classification method, while the PSD is merely a check.

4.4.2 Results

The classification procedure was checked against the researcher's own manual classification and the degree to which the two agreed was noted. It was found that there was a 63% match. That is, 63% of the sounds were classified the same by both the automated procedure and the researcher.

Errors in the classification of the signals resulted from a number of different sources:

- Occasionally, noise in the recording would produce a spike and this would be noted as a sound and duly removed and analysed. This resulted in an incorrect classification.
- When the differences between the wavelet co-efficient values were small, a misclassification could occur.
- A small number of recorded sounds did not fit any of the classes. These were disregarded as outliers for the purpose of this experiment.

Despite these errors, the rate of correct classifications is a promising result, which indicates that the characteristics identified can be utilised in the development of a fully automated sound detection and classification system, which may use more sophisticated signal processing and decision making techniques.

4.5 Sound-Condition Correlations

It was considered that the sounds recorded might be linked to various conditions. These conditions were related to both the imlant and the patients, and are listed in Section 1.1. In order to determine whether or not any links existed, two factors were investigated, namely:

- sound occurrence: the number of sounds identified in each recording.
- wavelet characteristics of the sounds: in order for this to be considered viable, the wavelet decompositions of all sounds would need to be re-examined and reliable trends identified.

4.5.1 Body Mass Index Correlation

The Body Mass Index (BMI) is a measure used to give an individual's weight in relation to their height. It can be used to identify whether or not their weight is healthy or unhealthy and therefore indicate health risks. It is calculated using equation 4.2 below [49]:

$$BMI = \frac{mass(kg)}{height^2(m^2)} \tag{4.2}$$

The BMI is placed into one of the categories given in Table 4.3 below, which identifies the category a given patient falls into:

Table 4.3: BMI categories

BMI	Category
x $\leq$ 18.9	underweight
19 $<$ x $\leq$ 24.9	normal
25 $<$ x $\leq$ 29.9	overweight
x $\geq$ 30	obese

Wavelet Characteristics

In order to identify whether any correlation exists between the sounds produced and each participants BMI, the wavelet decompositions of the sounds from individuals in each category were analysed. This analysis was the same as that described in Section 4.3. That is, the wavelet levels, and their FFTs were inspected for similarities in their frequency content. However, no reliable trend could be detected.

It was of interest to know whether the occurrence of each of the sound classes, defined in Section 4.3, might be used to determine which BMI category an unanalysed recording falls into. Such a procedure would be based upon the number of times certain wavelet characteristics were identifed in an unknown sound. In order to do this, the number sounds in each class was counted to identify whether any pattern could be identified.

Table 4.4: BMI-sound class correlation

BMI	No. in group	Clunks (per person)	Clicks (per person)	Knocks (per person)
underweight	4	9 (2.25)	1 (0.25)	1 (0.25)
normal	20	30 (1.5)	8 (0.41)	21 (1.05)
overweight	24	52 (2.17)	22 (0.92)	16 (0.67)
obese	39	60 (1.54)	28 (0.72)	36 (0.92)

As can be seen, both normal and obese groups have the the most clunks, then knocks, then clicks per person. Therefore automated signal detection would not be able to tell which of these two categories a signal with this pattern would fall into. The overweight group has the most clunks, then clicks, then knocks. This pattern is distinct from the other groups.

Sound Occurrence

The higher a patient's BMI, the higher their risk of various illnesses. As part of this experiment, it was of interest to find out whether or not there was a link between a patient's BMI and the occurrence of sounds produced by their implant. In order to achieve this the patients were sorted into their BMI categories and the number of sounds in each of their recordings was counted.

In order to identify which of the four categories produced the most sounds, the noise levels in each patient's recordings were noted and the number of individual sounds that were heard was recorded. The number of sounds was then averaged to determine the average number of sounds per person per category. These results are given in Table 4.5.

Table 4.5: BMI Results

BMI	No in group	No who reported sounds	No who actually had sounds	Total no of sounds	Average no of sounds per movement	Average no of sounds per person
Underweight	4	1 (25%)	4 (100%)	14	4	4
Normal	20	5 (25%)	19 (95%)	64	16	3
Overweight	24	5 (21%)	23 (96%)	101	25	4
Obese	39	6 (15%)	37 (95%)	131	33	4

The category with a BMI greater than 30 has the highest level of sounds. This shows that there may be a link between a higher BMI and a higher sound occurrence.

4.5.2 Implant Angle Correlation

Correct positioning of the hip implant is extremely important to ensure stability. If this is not maintained the implant may be prone to dislocation and the patient may experience a decreased range of hip joint motion [50–52]. Of particular importance in avoiding these problems is the positioning of the acetabular component. This is maintained through the angles of anteversion and inclination (also known as the abduction angle). The angle of inclination is the angle the acetabular cup forms with the horizontal axis. The angle of anteversion is the forward-facing angle the acetabular cup forms with the vertical axis. The optimal range for these are an anteversion of $15° \pm 10°$ and and inclination of $40° \pm 10°$. Implants with angles within these ranges show a decreased rate of dislocation [53].

Wavelet Characteristics

The wavelet decompositions of the sounds recorded from the participants falling into each category were examined. This was done to determine whether or not any similarities between them could be detected. The frequency content of all wavelet levels were compared, as was described in Section 4.3. However, no reliable trends were apparent.

It was of interest to know whether the occurrence of each of the sound classes, and their accompanying wavelet characterisitcs as defined in Section 4.3, might be used to determine which implant angle category an unanalysed recording falls into. In order to do this, the number of sounds in each class was counted to identify whether any pattern could be identified.

Table 4.6: Inclination-sound class correlation

Inclination (°)	No in group	Clunks (per person)	Clicks (per person)	Knocks (per person)
Below 30	1	4 (4)	0 (0)	0 (0)
30 to 40	24	58 (2.42)	21 (0.88)	27 (1.13)
40 to 50	52	77 (1.48)	32 (0.62)	34 (0.65)
Above 50	14	15 (1.07)	9 (0.64)	12 (0.86)

Hip implants with inclination angles between 30° and 40° have the most overall sounds per person and this makes this group stand out. Both the 40° to 50° group and the above 50° group have wavelet occurrences that can be ordered clunks-knocks-clicks and therefore this alone cannot be used to distinguish them from each other. However the 40° to 50° group has more clunks while the above 50° group has more knocks. In order to use this information to classify a recording, one would need multiple recordings to compare it to. Therefore, this information on its own is not sufficient to classify an unknown recording.

Table 4.7: Anteversion-sound class correlation

Anteversion (°)	No in group	Clunks (per person)	Clicks (per person)	Knocks (per person)
0 to 5	12	19 (1.58)	6 (0.5)	6 (0.5)
5 to 15	37	72 (1.95)	29 (0.78)	40 (1.08)
15 to 25	31	36 (1.16)	18 (0.58)	21 (0.68)
Above 25	11	26 (2.36)	9 (0.82)	7 (0.64)

With regards to anteversion angles, the group which has the lowest number of clicks and knocks is the 0° to 5° group and this may also be used to tell this group apart from the others. The above 25° group has the the most clunks and clicks while the 5° to 15° group has the most knocks. Both the 5° to 15° group and the 15° to 25° group have wavelet occurrences that may be ordered clunks-knocks-clicks and therefore this cannot be used to separate them. However, the 5° to 15° group has more sounds per person overall. As with the inclination angles, this information on its own is not enough to classify an unknown recording.

Sound Occurrence

In order to identify whether or not a link existed between the implant angles and the levels of sounds produced by the implants, the angles of each of the patients' implants were measured and the patients were then sorted into the various categories of angles. The number of sounds in each of their recordings was then counted and the noisiest group was identified. The results are given in Tables 4.8 and 4.9 below.

In the case of the angle of inclination, the majority of sounds occured in the group whose angles fell in the upper limits of the normal range. In the case of the angle

Table 4.8: Inclination Angle Results

Inclination Angle (°)	No in group	No who reported sounds	No who actually had sounds	Total no of sounds	Average no of sounds per movement	Average no of sounds per person
Below 30	1	0 (0%)	1 (100%)	4	1	4
30 to 40	24	3 (13%)	24 (100%)	111	28	5
40 to 50	52	10 (19%)	48 (92%)	160	40	3
Above 50	14	4 (29%)	12 (86%)	38	10	3

Table 4.9: Anteversion Angle Results

Anteversion Angle (°)	No in group	No who reported sounds	No who actually had sounds	Total no of sounds	Average no of sounds per movement	Average no of sounds per person
0 to 5	12	1 (8%)	12 (100%)	31	8	3
5 to 15	37	7 (19%)	35 (95%)	145	36	4
15 to 25	31	6 (20%)	28 (90%)	86	22	3
Above 25	11	3 (11%)	10 (91%)	51	13	5

of anteversion, the most sounds were identified in the group whose angles are in the lower limits of the noraml range. However, neither can be individually isolated as a cause of the sounds since sounds were identified in almost all members in all the groups.

In order to completely determine the effect of the angles, they must be considered together. One is held constant in the optimal range and the other is varied to determine the number of sounds that are identified.

4.5.3 Implant Age Correlation

In the same way as natural hips degenerate, so too do hip implants. However, the nature of the wear is very different. Stripe wear due to repeated movements and friction between the articular surfaces are major causes of wear and tear on the implant. As the implant ages it is theorised that the sounds produced by the implants may change or worsen.

Wavelet Characteristics

The wavelet decompositions of the sounds recorded from the participants falling into each category were examined. This was done to determine whether or not any similarities between them could be detected. The analysis was aimed at finding possible trends in the frequency content of the signals and thus was the same as was described in Section 4.3. However, no reliable trends were detected.

As was the case with previous patient factor groups, occurrence of each of the sound classes was determined. This was done to determine whether the occurrence of certain wavelet characteristics, as identified in Section 4.3 above, might be used to determine which implant age category an unanalysed recording falls into. In order to do this, the number of sounds in each class was counted to identify whether any pattern could be identified.

Table 4.10: Implant Age-sound class correlation

Implant Age (months)	No in group	Clunks (per person)	Clicks (per person)	Knocks (per person)
0 to 12	9	15 (1.67)	6 (0.67)	9 (1)
12 to 24	26	48 (1.85)	23 (0.89)	25 (0.96)
24 to 36	27	70 (2.59)	16 (0.59)	23 (0.85)
36 to 48	12	20 (1.67)	8 (0.67)	7 (0.58)
Above 48	17	20 (1.18)	9 (0.53)	10 (0.59)

In this instance, the only group with more clicks than knocks per person is the 36 to 48 month age group. The other groups have more knocks than clicks per person. All groups have high numbers of clunks per person. This information on its own is therfore not enough to allow for automated classification of an unknown recording.

Sound Occurrence

In order to test whether the frequency or amplitude of the sounds increased with age, the age of each of the implants studied was calculated and the number of sounds produced by each was tallied. The results are given in Table 4.11.

Table 4.11: Implant Age Results

Implant Age (months)	No in group	No who reported sounds	No who actually had sounds	Total no of sounds	Average no of sounds per movement	Average no of sounds per person
0 to 12	9	3 (33%)	9 (100%)	30	8	3
12 to 24	26	6 (23%)	26 (100%)	100	25	4
24 to 36	27	5 (19%)	24 (89%)	103	26	4
36 to 48	12	1 (8%)	11 (92%)	38	10	4
Above 48	17	2 (12%)	15 (88%)	43	11	3

The age of the implant was measured in months from the date of the initial implant operation. The group that produced the most sounds was the 24 to 36 month group. Considering implant age on its own, no correlation is evident. The sounds do not appear to worsen or become more prominant or regular with increasing implant age. However, in order to completely validate this, a long term study would need to be performed. This could involve measuring the sounds from patients every 12 months, at their annual follow-up, from the time of their initial operation. The sounds could then be compared to determine any changes.

4.5.4 Bearing Surface Combination Correlation

This study would like to try to identify which of the bearing surface combinations currently in use produces the most sounds, and if it is possible to distinguish between combinations based on the sounds. To that end, the participants were divided into four groups, depending on the combination they had, and the total number of sounds produced in each group were counted. The results are shown in Table 4.12.

Table 4.12: Bearing Surface Combination Results

Combination	No in group	No who reported sounds	No who actually had sounds	Total no of sounds	Average no of sounds per movement	Average no of sounds per person
CoC	22	8 (36%)	20 (91%)	81	20	4
CoM	26	5 (19%)	25 (96%)	83	21	3
CoP	21	3 (14%)	20 (95%)	79	20	4
MoM	22	1 (5%)	20 (91%)	71	18	4

As was seen from the signal analysis, there does not appear to be a way to distinguish the bearing surfaces based on the sounds themselves. However, all bearing surface combinations produce sounds, and they can be ordered in terms of which combination produces the most sounds. This order is: CoM - CoC - CoP - MoM. The hard combinations thus produce the most sounds, which is in line with current knowledge.

The group sizes vary due to the random manner in which the participants were recorded. It is noted that, although the CoM group has the largest number of participants, the average number of sounds per movement is not significantly larger than that of the CoC group. However, as has previously been stated, it is possible that the group with the largest number of members will dominate the total tally.

Wavelet Characteristics

As with previous conditions examined, it was of interest to know whether or not any frequency similarities could be detected in the sounds of the participants falling into each category. To determine this, the wavelet decompositions of the sounds were examined. The FFTs of each wavelet level was also investigated to identify whether any trends could be found. However, no reliable patterns could be identified. Therefore, no differences between the frequencies contained in the sounds from different groups could be detected.

4.5.5 Sound Class Prevalences

In order to determine which of the sound classes were the most dominant, the total number of sounds heard during analysis were counted. These were compared to the number of sounds reported by the patients in their questionnaires. The results are given in Table 4.13 and 4.14.

Table 4.13: Total Sound Class Occurrences from Signal Analysis

Combination	No in Group	Clunks	Clicks	Knocks	Grating	Compound
CoC	22	33	19	22	4	3
CoM	26	42	16	22	3	3
CoP	21	34	18	20	2	7
MoM	22	44	9	10	7	3

It can be seen that clunks are the dominant sound class across all four bearing surface combinations, although they occur most frequently in the MoM group. Clicks are most prevalent in the CoC group with knocks being equally prevalent in the CoC and CoM groups. Grating and compound sounds occur the least in all four bearing surface combinations.

This class prevalence could also be used to determine whether or not the wavelet characteristics of each class, defined in Section 4.3, could be used to classify an unknown recording into one of the bearing surface combination groups. The difference in occurrence patterns between the bearing combination groups means that it is possible to classify an unknown recording into one of these groups, based on the occurrence of the wavelet characteristics of the isolated sounds.

Table 4.14: Total Sound Class Occurrences Reported by Patients

Combination	No in Group	Clunks	Clicks	Knocks	Grating	Compound
CoC	22	0	4	0	2	0
CoM	26	1	2	0	1	0
CoP	21	2	2	0	0	0
MoM	22	0	1	0	0	0

The most frequently reported sounds are clicks, regardless of the bearing surface combinations. This indicates that clicks are the most readily audible.

4.6 Sound - Movement Correlation

The participants performed simple, everyday movements. This was because they were movements that everyone would perform many times in a day and would therefore be responsible for the greatest degree of wear and tear on the implant. Any patterns in the sounds that were produced by these movements were also identified and paired up with videos made of the participants while they performed the movements. In order to determine which sound class occurs most frequently and which movements produce which sounds the movement recordings were analysed and the sounds occuring in them were identified. The number of times each class occured was then counted. The results are shown in Table 4.15.

Table 4.15: Sounds occuring in each movement

Movement	Clunks	Clicks	Knocks	Grating	Compound
Walking	49	21	17	6	7
Climbing Stairs	52	17	19	3	3
Sitting	32	12	17	4	6

Clunks were found to occur the most frequently, followed by clicks and knocks. The most clunks occured while climbing stairs. The most clicks occured while walking. The most knocks occured while climbing stairs. In many cases, the movement produced multiple sounds of more than one class. This is distinct from compound sounds.

4.7 Interdependence of the Conditions

Considering the conditions individually shows that they each have a possible link to the production of sounds. However, each identifies individual criteria, and each produces a different result. This is highlighted when all the factors are combined and considered together. In order to accurately quantify the effects of each of the factors, one would need at least one implant with the perfect combination of all factors to be considered and then identify the effects of varying each of the factors individually. This implies that only one factor would be varied at a time. This is very difficult to achieve in a clinical environment.

It can therefore be stated that this is a complex problem involving many interdependent factors. Various combinations of the different factors would need to be considered in order to determine which one was dominant. The study would also need to take place over a longer time period. In addition, the number of study participants would have to increase substantially to make any conclusions statistically significant.

4.8 Conclusion

It has been shown that the sound recordings made from artificial human hip implants contain large amounts of information. The issue of retrieving that information and interpreting it has been the focus of this chapter. To that end, signal analysis techniques were investigated and applied to the recorded signals to isolate individual sounds. This was successfully achieved and a number of separate sound classes were identified. The signal analysis techniques were then employed to identify and classify sounds in previously unanalysed recordings. This was achieved, with partial success, therby indicating that this procedure could feasibly be applied to the detection and classification of hip implant sounds.

It was also of interest to determine whether any links between the sounds produced and external factors could be identified. It was noted that there are many factors that may influence the production of sounds by implants. It was also noted that as all these factors are interlinked it is extremely difficult to isolate one factor as being the dominant one. In order to exactly quantify the effects of one particular factor, the others would all have to be both optimal and constant, two things that are very difficult to achieve.

Chapter 5

Conclusion

Hip implants have been the primary method of treatment for hip injuries and osteoarthritis. Many patients have reported hearing sounds emitting their hip implants, which prompted a number of investigations focused on determining the cause of these sounds and their significance.

The purpose of this study is to determine whether such sounds could be of use to medical professionals when monitoring and determining the health of hip implants within a patient. To achieve this, the sounds emitted by hip implants were recorded and subsequently analysed. These results were used to determine whether any relationship exists between such sounds and the different types of bearing surface combinations used in hip implants, a patient's body mass index, an implant's angle, the age of the implant, and the movement performed by a patient.

The following subsections summarise the methodology used record and analyse sounds emitted by hip implants, the key contributions made to the field of hip implant sound analysis, and identifies some areas for future research.

5.1 Methodology and Results

One of goals of this study was to design a method of reliably recording sounds which can provide medical practitioners with a relatively simple and non-invasive method to monitor and determine the health of a hip implant. An electronic stethoscope was chosen to fulfil this purpose, as it meets these criteria and also possesses the benefits of being readily available to medical practitioners and performing well in comparison to custom diagnostic equipment.

Although the electronic stethoscope was well suited to recording the sounds emitted by hip implants, particularly as it captures a range of sounds that include those outside the audible range, its sensitivity to background electrical noise and pressure placed on the probe proved problematic. In addition, the large amount of signal analysis required before useful information can be extracted from the recorded signals proved that while the system was reliable, it was also impractical as a real-time diagnostic technique.

Data to be analysed was collected from individuals with hip implants. Participants were randomly chosen from a predefined group from a previous study and they were interviewed when they went for their regular follow-up appointments.

Digital signal processing techniques were used to analyse the recorded sounds and attempt to determine the relationship between specific components within the signals and possible causes of the sounds within a hip implant. A number of different techniques were implemented to test their suitability and determine whether they could extract useful information from the recorded sounds. These signal processing techniques included digital filters, spectrograms, the discrete wavelet decomposition and Welch power density spectra.

The Savitzky-Golay filter was used to remove unwanted background noise, while the discrete wavelet decomposition allowed for different classes of sounds to be identified based on their frequency characteristics. This analysis was confirmed through the use of Welch power spectral density plots, after which the sounds were grouped into classes based on common signal characteristics.

The characteristics that were identified were used to identify and classify sounds in previously unanalysed recordings. A step-by-step procedure was used to implement this and it was successful in its application.

To determine the significance of sounds emitted by hip implants the sounds' signal characteristics were compared with the conditions of the implants and various patient factors. These included the age and positioning of the implant, the BMI of the patient and the bearing surface combination. After a rigorous analysis of the recorded sounds, it was determined that no direct relationship exists between these factors and the signal characteristics of the recorded sounds. However, partial success was obtained in using the occurrences of the sound classes, and their corresponding wavelet characteristics, to determine which of the patient factor groups a sound belonged to.

A lack of correlation between sound occurrence and implant age indicates that this technique is not useful in predicting possible failure or complications, although it was determined that patients with a higher BMI did experience a higher occurrence of sounds emitted by hip implant.

5.2 Key Contributions

The purpose of this study is to record and analyse the sounds emitted by hip implants and thereby determine the significance of such sounds. The key contributions made by this study to the field of hip implant sound analysis are summarised as follows:

- During the course of this study, a number of different classes of sounds were defined, with each class containing specific acoustic characteristics which correlated with their signal characteristics. This class-based system forms the basis of a new and unique system for the classification of sounds emitted by hip implants.
- The signal definitions were successfully able to identify and classify individual sounds in previously unanalysed recordings. This shows that the signal analysis data gained is useful in both identifying sound occurrences as well as determining which sounds are present.
- Based on the occurrence of each of the predefined classes of sounds, and their corresponding wavelet characteristics, in an unknown recording, it is possible to identify which of the bearing surface combinations studied the unknown recording may have originated from. It was also possible to distinguish between the overweight BMI, which had a distinct wavelet occurrence pattern, and the underweight and obese BMI categories, which had a similar wavelet occurrence pattern.
- A reliable, simple and non-invasive method for recording and analysing sounds emitted by hip implants was developed. Prior to this study no such method existed. Data collected for research relied on expensive, custom designed equipment which was not readily available, thus limiting research possibilities.

The objectives specified in the problem statement in Chapter 1 were investigated. The knowledge gained from this study is expected to contribute to the improved understanding of the causes of sounds emitted by hip implants, which in turn will aid in the monitoring and treatment of these patients.

5.3 Future Work

This study makes a contribution to the field of hip implant sound analysis and also helps identify some areas for focused future research. These are listed below:

- Signal analysis techniques - a number of signal analysis techniques were tested to determine whether they are effective when identifying sounds in hip implant recordings. New or different signal analysis techniques could be applied to the same problem, and results compared to those of this study, to determine whether they are more or less effective.
- Signal classification - Artificial intelligence methods could be used to produce a more rigidly workable and more accurate classification system. This was done merely to determine whether or not any data could be gained and whether this data could be used. It has been shown that this can be done and therefore a more formal classification technique could be employed. Possibilities include neural networks or fuzzy logic, which allows for a greater degree of variability in the classification criteria.
- Sound-movement localisation - this study has demonstrated that routine everyday movements produce sounds from the implants. Detailed goniometric analysis of the movements would be useful in localising the point within each movement at which the sound occurs. This could assist in the identification of mechanical and placement factors that may be the cause of the sounds.
- Natural hips - this study only considers the sounds produced by hip implants. It would be of interest to compare these noise levels to those of healthy natural hips and identify the different sound characteristics.
- Larger sample group - the conclusions reached in this study are valid for the group of participants. A larger sample group would need to be evaluated for a longer period of time in order to confirm the results and thereby ensure statistical validity.

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Appendix A

Wavelet Analysis Figures

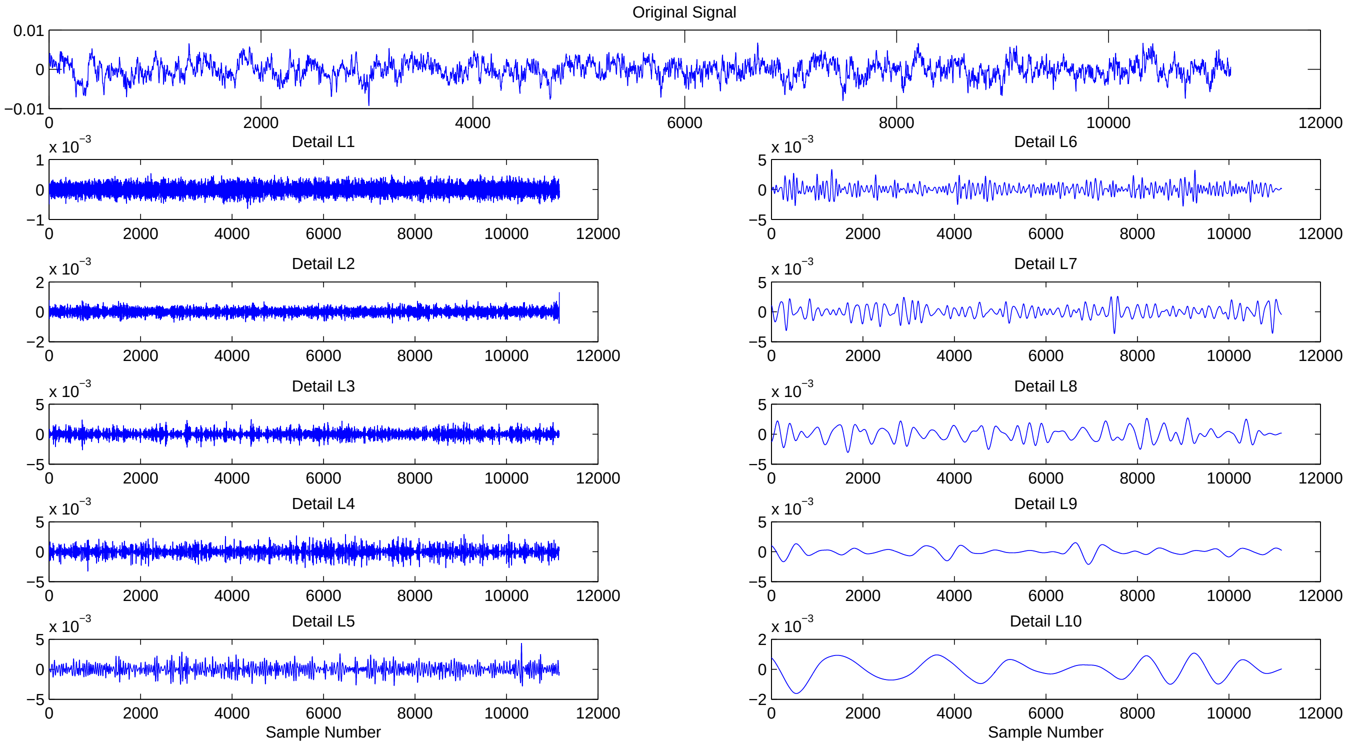

Figure A.1: Class 1 Wavelet Decomposition

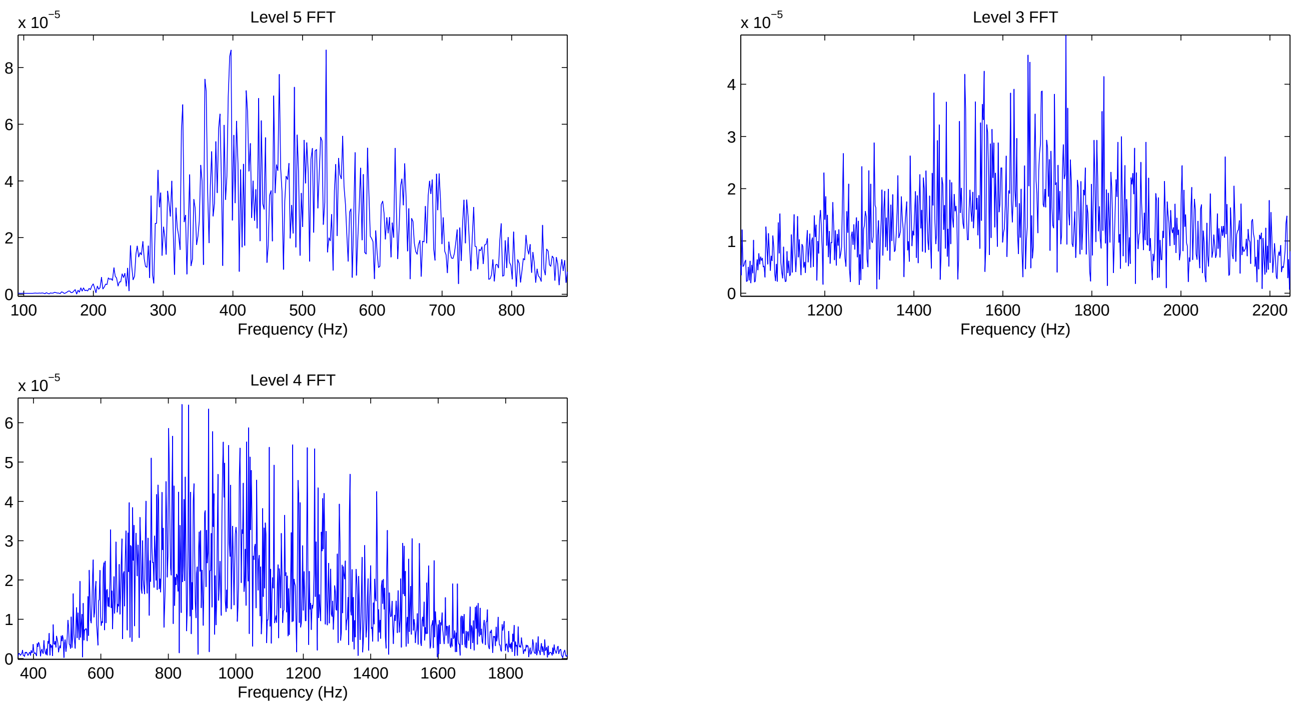

Figure A.2: Class 1 Wavelet Decomposition: Level Fast Fourier Transforms

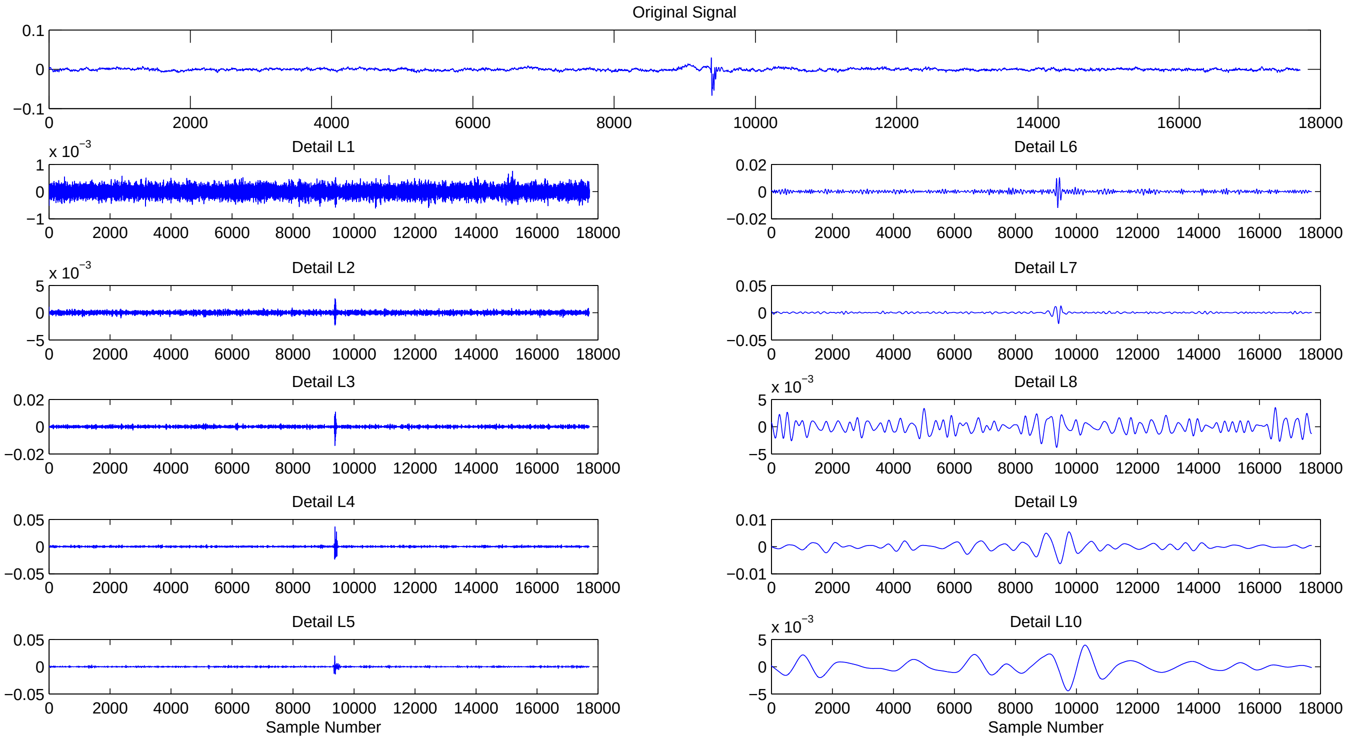

Figure A.3: Class 2 Wavelet Decomposition

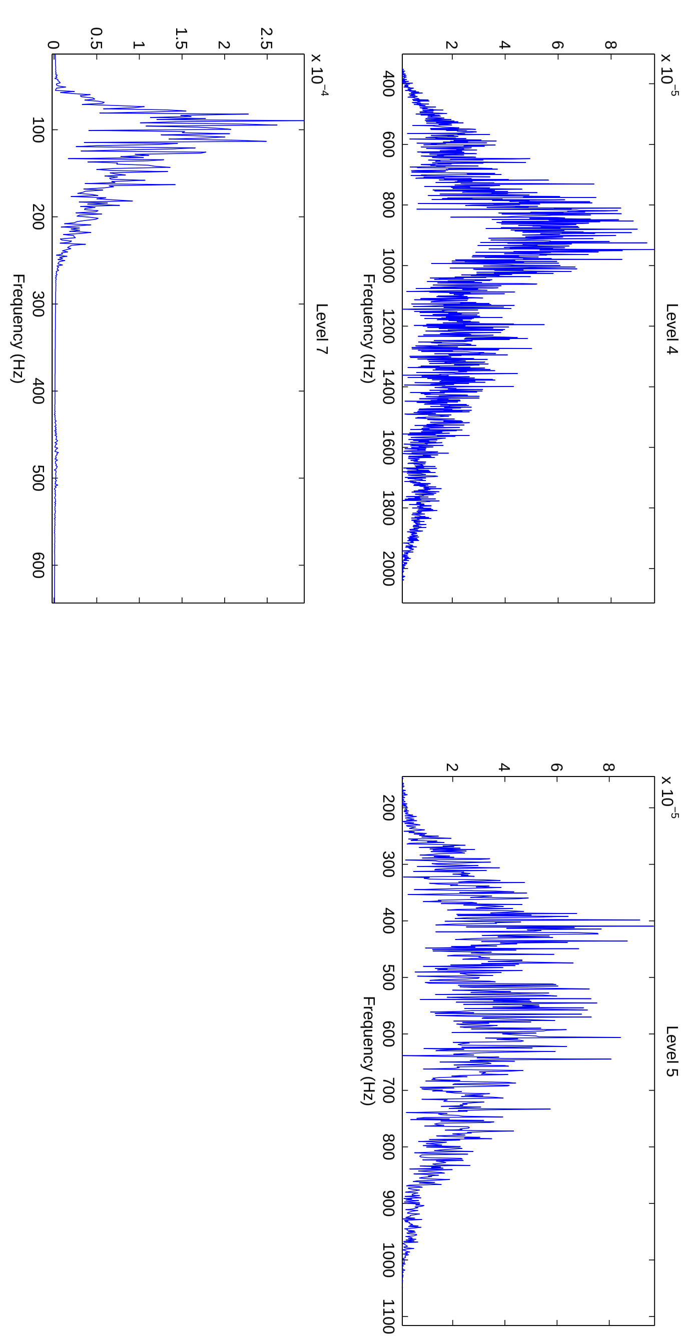

Figure A.4: Class 2 Wavelet Decomposition: Level Fast Fourier Transforms

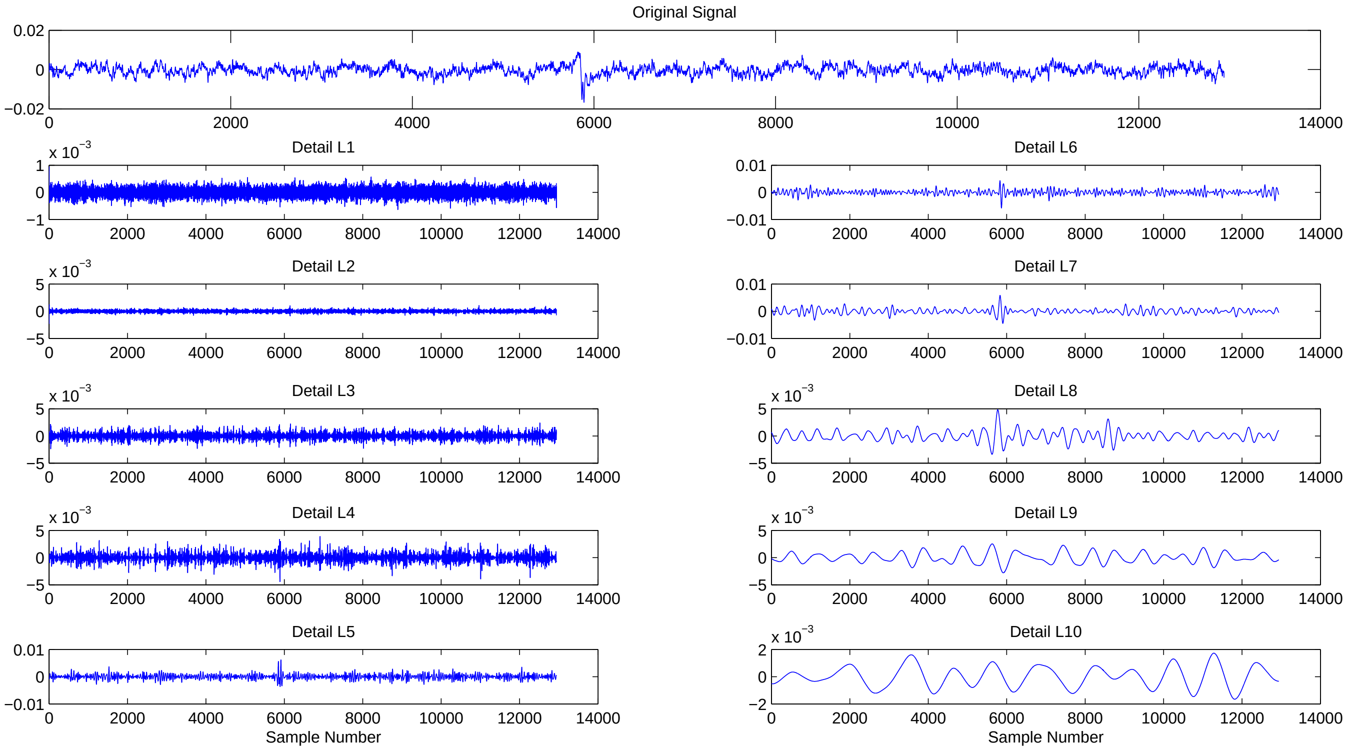

Figure A.5: Class31 Wavelet Decomposition

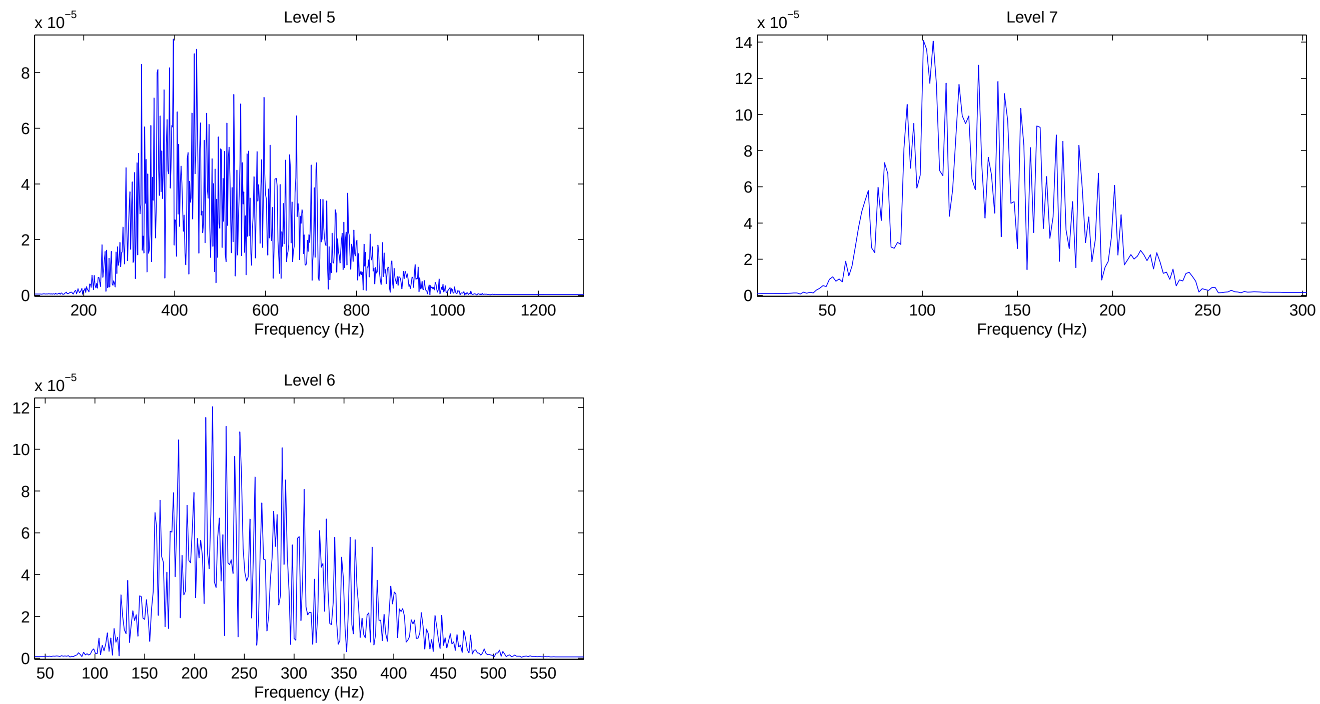

Figure A.6: Class 3 Wavelet Decomposition: Level Fast Fourier Transforms

Appendix B

Ethics Clearance Certificate

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Division of the Deputy Registrar (Research)

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
R14/49 Miss Helen R Wright

CLEARANCE CERTIFICATE **M090456**

PROJECT Determination of the Acoustic Characteristics of Artificial Human Hip Joints

INVESTIGATORS Miss Helen R Wright.

DEPARTMENT School of Electrical & Information Engineering

DATE CONSIDERED 09.04.29

DECISION OF THE COMMITTEE* Approved unconditionally

Unless otherwise specified this ethical clearance is valid for 5 years and may be renewed upon application.

DATE 09.07.24 **CHAIRPERSON** ....
(Professor PE Cleaton-Jones)

*Guidelines for written 'informed consent' attached where applicable

cc: Supervisor : Dr D Rubin

DECLARATION OF INVESTIGATOR(S)

To be completed in duplicate and **ONE COPY** returned to the Secretary at Room 10004, 10th Floor, Senate House, University.
I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to resubmit the protocol to the Committee. **I agree to a completion of a yearly progress report.**

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES...

Appendix C

Participant Documentation

Patient Information Leaflet

Title: Determination of the acoustic characteristics of artificial human hip joints

Introduction

Good day. My name is Helen Wright. I am a postgraduate student in the School of Electrical and Information Engineering at the University of the Witwatersrand. I would like to ask you to consider participating in a research study entitled:
Determination of the acoustic characteristics of artificial human hip joints

Why is it necessary to do such a study?

Noises have been reported in all bearing surface combinations. It is necessary to do this research in order to determine the exact characteristics of the sounds produced by hip implants. This data can then be used to predict how long the implant will last.

Invitation

You are being invited to take part in a research study. Before you decide it is important for you to understand why the study is being done and what it will involve. Please take time to read the following information carefully and ask me if there is anything that is not clear to you.

Purpose of the Study

I am measuring the sounds produced by hip implants. This is so that I can determine whether or not these noises are produced by all different types of implants and what the exact characteristics of the sounds are. This is useful because it is possible that these sounds may be related to the age of the implant. Therefore this data may be used to predict how much longer the implant will last.

Taking Part

The decision to take part in the study is entirely voluntary. If you decide to take part you will be given this information sheet to keep and you will be asked to sign a consent form. I am asking for your consent because the study will involve the collection and recording of data on the functioning of your new hip. You are free to withdraw from the study at any time without giving a reason.

In taking part in the study you will have a microphone attached to your hip. You will be asked to perform a variety of different movements. You will be asked to walk a distance of three complete gait cycles, climb a flight of stairs and sit down in a chair. The sounds made by your hip joint while you are moving will be recorded and used for signal analysis. You will also be video taped while performing these actions. Your age, gender, type of hip prosthesis, time since implant, weight and height will be recorded for correlation purposes. Digitised copies of existing X-rays will also be utilised to make appropriate measurements on the implants. You will not need to have more X-rays done.

All this will be done during one of your routine visits to the hospital so you will not be required to make special trips. The recording process will take an estimated time of an hour and a half.

Risks

This study poses no foreseeable risk to you.

Ethical Approval

This research study protocol has been submitted to the University of the Witwatersrand Human Research Ethics Committee – awaiting approval. This study has been structured in accordance with the Declaration of Helsinki, which gives guidelines that must be followed when conducting biomedical research involving human subjects.

Confidentiality

The information may be used in scientific presentations and be published in scientific journals. However confidentiality will be maintained at all times and no publication will refer to any patient by name.

Reimbursement for Participating in the Study

You will not be paid to participate in the study.

Patient Study Number:____________________

Patient Consent Form

Title: Determination of the acoustic characteristics of artificial human hip joints

I, ____________________ (patient name) confirm the following:

I hereby confirm that I have been informed about the nature, conduct, benefit and risks of the above mentioned study.

I have received, read and understood the Patient Information Leaflet for this study.

I am aware that some of my personal details such as age, gender, diagnosis and other relevant information will be processed into a study report, on an anonymous basis.

For the purposes of the research project I agree that the data collected during this study can be processed by a research assistant working for the investigator.

I may withdraw my consent and participation at any stage without prejudice.

I have had sufficient opportunity to ask questions.

I declare myself prepared to participate in the study of my own free will.

____________________ ____________________

Signature Date

I, ____________________ (researcher) herewith confirm that the above patient has been fully informed about the nature, conduct and risks of the above study.

____________________ ____________________

Signature Date

Patient Study Number:____________________

Patient Questionnaire

Title: Determination of the acoustic characteristics of artificial human hip joints

Date: ____________________

Consent given: YES / NO (if NO, do not proceed)

Questions

Date of hip implant surgery: ____________________

Side on which hip was replaced: RIGHT / LEFT

Does your replaced hip make a noise? YES / NO

If the above answer is yes, what sort of noise is it?

Clunk

Click

Squeak

Pop

Other – please describe:

____

What kind of movement results in the noise?

Walking

Rising from a seated position

Crouching onto haunches

Climbing stairs

Lifting the operated leg

Shifting the pelvis from side to side

Other – please describe:

____

How soon after the operation did you start hearing the noise?

____

Is the noise constant or random? ____

Has the noise changed or worsened in any way? YES / NO

If the above answer is YES, please describe: ___________________________________

____

____

____

Are you still hearing the noise? ____

Any further comments: ____

____

____

____

____

Thank you for your time