PASSIVE ACOUSTIC SENSING FOR THE ASSESSMENT OF KNEE CONDITIONS

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ABSTRACT

Early detection and diagnosis of knee related health disease is critical in mitigating the long term health risks of such ailments. Passive acoustic sensing is an under-utilized monitoring system that can be used in the assessment and potential diagnosis of knee health that has many potential benefits when compared to current medical technology. Developing accurate acoustic models and procedures for analyzing acoustic sensor data in these applications is of great importance. This paper presents the design and development of passive acoustic sensing system for characterizing knees along with data analysis techniques towards this end.

INTRODUCTION

Knee joint related health issues are a serious affliction for a substantial portion of the population. The most common disease is knee osteoarthritis, which results in the degeneration of articular cartilage in the knee joint, consequently increasing stress on the knee while in motion. An accurate diagnosis and assessment of osteoarthritis is becoming increasingly important. Typical methods of diagnosing knee osteoarthritis are knee arthroscopy, CT scan, and magnetic resonance imaging (MRI). In addition to the high costs, these imaging modalities require the patients to be in stationary positions and postures, limiting the scale and scope of the assessments.

The direct complications of osteoarthritis are due to the induced stress, resulting acoustic emission during motion. Thus, passive acoustic sensing can be a simple and effective approach to the accurate assessment of the condition of the knee. The data acquisition and signal processing of the laboratory prototype is supported by a smart phone and a wideband microphone. The utilization of the smart phone allows us to conduct data acquisition while the knee is in motion to provide a full-range assessment at various stress levels. Its video capability provides synchronized correspondences between the physical positions of the knee and the acoustic data sequences. The embedded signal-processing capability facilitates real-time analysis of the acoustic signals. The portability of the smart phone also enables us to monitor the condition of the knees on a frequent and regular basis for the detection of changes and abnormalities. Short-time Fourier Transform (STFT) is utilized to analyze the spectral variation corresponding to different angular positions of the knee. The time varying statistics of the
acoustic signals were also processed as a means to characterize knee condition. Multiple features present in the spectrograms and statistics were examined as possible indicators of the health of the knee joint.

**BACKGROUND**

Prior research has been performed on the acquisition of knee acoustic signals and their classification. The anatomical construction of the human knee joint includes the femur, tibia, and patella bones insulated from one another by the articular and meniscal (meniscus) cartilage as seen in Figure 1. The cartilage cushions the bones in the joint as the knee bends and straightens as well as reduces overall friction during movement. Knee osteoarthritis is the degeneration of this cartilage, which decreases the lubricated area between the bones. The tibia and femur will began to rub up against one another causing significant pain to the patient as well as possible long term damage in the process.

Figure 1: Anatomical View of the Human Knee

The major cause of knee osteoarthritis is attributed to long term wear and tear damage on the knee joint, and although it is most common in older patients it also can afflict people who are obese, work jobs that put repeated stress on the knee joint, or suffered knee injuries. As the general aging of the population occurs and obesity rates in many countries increase, knee osteoarthritis has become a serious public health concern. Due to the long term nature of the disease early detection is critical for mitigating its effects on patients. Treatments range from lifestyle changes to full replacement surgery, but once the cartilage has begun deteriorating there are no permanent treatments.

The main diagnostic tools today used by clinicians have drawbacks that limit their effectiveness to treat patients. Invasive techniques such as knee arthroscopy with surgical cameras have been successful in diagnosis of knee osteoarthritis, however, the surgical risks can be high for many patients and should be left as a last resort. The imaging based techniques (X-Ray, CAT scan, MRI) have limited detection capabilities especially during the early stages of the disease. Symptoms of knee osteoarthritis often manifest themselves while the joint is in motion, but the static nature of the imaging techniques limits their ability to capture this information as signs of
the disease. All of these medical procedures are also of high cost and immobile and are not well suited for in-home health care applications that much of the older population require.

Acoustic detection and diagnosis of knee osteoarthritis can provide a noninvasive, inexpensive solution that is also mobile. The lack of cartilage in the knee joint will generate friction between the bones whenever the joint is in motion and the acoustic signal emitted from the friction source could serve as a discriminating biomarker for knee osteoarthritis.

Much research has been performed on the auscultation of knee acoustic signals. Previous researchers have deployed various acoustic transducers as well as vibroarthrographic sensors to measure these signals. For vibroarthrography, researchers utilized small accelerometers coupled to the skin of the human knee to measure the vibrations produced within the joint. Many of the classification approaches of knee acoustic signals are based on highly mathematical and complex signal processing algorithms that often produce numerical results that can be difficult for a typical clinician to interpret. Data visualization of the knee acoustic signals, therefore, is a major need that can supplement much of the classification techniques developed prior.

Visualization of acoustic data has been a major issue in the field of speech processing. The Short Time Fourier Transform (STFT) is a classical speech processing tool that tries to capture the time-dependent frequency information of non-stationary signals. Knee joints with deteriorated cartilage in motion should also produce non-stationary signals that have specific spectral content present.

The non-stationary nature of these signals also indicates that the first and second order statistics of the acoustic signal would change over time. Specifically the second order statistics, or variance, of the acoustic signal would change over one cycle of knee motion. The sound of friction is a particular noisy signal with a relatively high variance. Therefore the short-time variance was also used as a metric for characterization of the knee.

**HARDWARE DESCRIPTION**

A series of experiments were conducted to test the effectiveness of acoustic based technology in measuring and characterizing knee acoustic signals for the goal of diagnosing cartilage degeneration in the knee joint. A data acquisition system was built from off-the-shelf components that were chosen based on their capability of measuring knee acoustic signals with high precision. The data acquisition system recorded acoustic data from test subjects who were asked to perform a specific movement task of the knee. A total of four subjects were studied with varying ages and knee related health status.

The data acquisition system was designed to maximize the probability of detection of knee acoustic signals as well as serve as a model for a low cost, portable diagnostic tool. The system was comprised of piezoelectric microphone, a mobile phone as the data recording system, and a PC laptop for performing the analysis computations. The microphone was attached to the test subject’s knee with hypo-allergenic medical tape and a layer of ultrasonic gel to minimize the acoustic impedance mismatch.
The Durham Instruments CM-01B Polyvinylidene Fluoride (PVDF) contact microphone was chosen as the acoustic transducer. The CM-01B microphone is a piezoelectric device that produces an electrical signal proportional to any pressure signal incident on its rubber surface, as seen in Figure 2. In the case of this experiment, the rubber surface was directly placed onto the knee surface so that the sensor is tightly coupled to any acoustic sources within the knee.

![Image](image.png)

Figure 2: (a) CM-01B Contact Microphone and (b) Frequency Response

The electrical signal is then passed through a broad-band transistor amplifier before being sent to the recording device. The audible frequency band of interest concerning knee acoustic signals is typically 100 Hz to 4 kHz. The frequency response of the CM-01B shown in Figure 4 (b) has a relative stable gain over this band. The Signal-to-Noise Ratio (SNR) was the other major design specification driving the choice of this microphone. The desired signal in this scenario is the sound produced by the knee, however, many other acoustic sources may be present in a medical environment that can be classified as noise. A typical electret or capacitive microphone will record from all directions; however, the CM-01B will only measure the vibration signal of the surface it is coupled with thus isolating it from superfluous noise sources and increasing SNR. The stable frequency performance and sound isolation properties of the CM-01B made it an ideal choice for the data acquisition system transducer.

To provide mobility for the data acquisition system, a Nexus 5 Android mobile device provided the data recording function. The Nexus 5 quantized the acoustic signal with a 14-bit ADC at a sampling rate of 44kHz. The data was saved as uncompressed audio in the PCM file format before being exported to a laptop PC. All data was processed and analyzed on the laptop PC in the MATLAB programming environment. However, the algorithms used were all of low complexity and with the increased computational capabilities of mobile devices full real-time data acquisition and analysis could be performed on the mobile device, removing the need for the PC.

EXPERIMENTS AND SUBJECT INFORMATION
A simple experimental procedure was designed for subjects to perform that would produce acoustic data that could be analyzed and compared across multiple participants. Acoustic knee signals are most likely to be produce while the knee joint is under a load. Therefore the procedure asked the subjects to stand up and down repeatedly to stress the knee joint. Each sit-stand movement cycle was broken down into three main phases: the initial extension of the knee from the sitting position, followed by the reaching of absolute extension, and finally the contraction of knee joint back into the sitting position.

Each subject was asked to perform this sit stand procedure 20 times, with the microphone attached to their knee. The placement of the microphone was placed below the outside of the patella, as this minimizes the anatomical distance to the bone contact of the human knee joint. Each experiment was video recorded to help correlate knee position with any acoustic signature.

In our experiment, three subjects in their twenties and one in his/her fifties were examined. Two of the patients both reported damaged to the meniscus in their knees. The subject information can be seen in Table 1.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Knee</th>
<th>Age</th>
<th>Report Health Issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Left</td>
<td>22</td>
<td>None</td>
</tr>
<tr>
<td>A</td>
<td>Right</td>
<td>22</td>
<td>None</td>
</tr>
<tr>
<td>B</td>
<td>Left</td>
<td>23</td>
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<tr>
<td>B</td>
<td>Right</td>
<td>23</td>
<td>None</td>
</tr>
<tr>
<td>C</td>
<td>Left</td>
<td>21</td>
<td>None</td>
</tr>
<tr>
<td>C</td>
<td>Right</td>
<td>21</td>
<td>Surgically Removed Meniscus</td>
</tr>
<tr>
<td>D</td>
<td>Left</td>
<td>56</td>
<td>Injured Meniscus</td>
</tr>
<tr>
<td>D</td>
<td>Right</td>
<td>56</td>
<td>None</td>
</tr>
</tbody>
</table>

ANALYSIS AND RESULTS

The final data set was comprised of two recordings of each subject (one for the right and left knee) for a total of 8 audio files each around 60 seconds in duration. The sampling rate was set at 44 kHz, which resulted in over 2.5 million data samples available for each acoustic signal.

The time domain data recorded from the left knee of Subject A is plotted in Figure 3. It can be seen that the signal is comprised of many short, transient acoustic emissions produced by the knee joint as it moved. It was determined that a typical movement cycle for the experiments lasted about 2.5 seconds and a two total movement cycles have been enlarged in the lower half of Figure 3. The length of one cycle varied across subjects, however, so two cycles of data was manually edited from each data set for analysis. The knee undergoes a full 180 degrees of angular displacement over the course of one movement cycle. The corresponding window length used for data processing was therefore set to 4096 samples, or about 100 ms, so that the angular resolution of each window was about 8 degrees.
The STFT can be expressed as:

$$X_R(e^{j\omega}) = \sum_{m=-\infty}^{\infty} x(m) w(n-m)e^{-j\omega m}$$

where $x(n)$ is the discrete time domain signal, $w(n)$ is the windowing signal and $\hat{n}$ is the window index. The equation computes the DFT of a windowed data frame extracted from $x(n)$ starting at the time index $n = \hat{n}$ to $n = \hat{n} + L$ where $L$ is the length in samples of each data frame. Each data frame was sent through a bandpass filter with cutoff frequencies of 100 Hz and 4 kHz to accentuate the audible frequency range in the spectrogram. The frames are sampled every $R$ samples, where typically $R < L$. A Hanning window was used for all STFT results. The STFTs were also normalized to unit magnitude to allow for direct comparison of the spectral energy across different signals.

Spectrograms of each data signal were carefully examined for visual features that could reveal physical information about the knee joint from which they were measured. By comparing the spectrograms with the video data collected during the experiments, specific features indicative of the knee joint’s position were identified. The spectrogram of four recordings is shown in the magnitude dB domain over 8 movement cycles of the knee joint in Figure 4. Each of the three movement phases are labeled in the spectrogram. As the knee joint is in its extension phase, the spectrogram exhibits numerous narrowband spectral peaks between 100 Hz and 500 Hz about 20-30 dB down from the highest peak. When the knee reaches the point of full extension a high amplitude wideband peak is visible from 100 Hz to 4 kHz. Then as the knee goes back into contraction, a strong but narrow spectral peak is present between 100 Hz to 1 kHz. Other various spectral features can be seen in the spectrogram, but these spectral characteristics were the most dominant features common in all the measured spectrograms and serve as a useful marker in analyzing knee acoustic signals.
As mentioned earlier, another potential marker for characterizing knee health was the variance of the signal. The variance of the signal was computed over two full movement cycles of the experimental data with the same window length used in the STFT results. The variance and spectrogram results for each subject are plotted in the figures below.

The first two figures are plots of the two relatively healthy subjects, whereas the second two were plots of the subjects who reported knee ailments. As can be seen in the plots, the signal variance picks up greatly for the knees with reported health issues in the center of the movement cycle. This would be the expected area of highest friction as the knee is under the most stress during this cycle. Subject D who reported knee damage yielded the highest signal variance of any subject, however, subject C who also reported a knee injury did not demonstrate a significant increase in signal variance. This may indicate that the age of Subject D significantly affected the cartilage content in the knee thus producing greater friction.
Figure 6: Subject A Left Knee (a) Spectrogram (b) Variance Signal

Figure 7: Subject C Right Knee (a) Spectrogram (b) Variance Signal

Figure 8: Subject D Left Knee (a) Spectrogram (b) Variance Signal
CONCLUSION

The ability to properly assess knee health in an economical and low risk manner is required to meet the growing challenges associated with knee related diseases. Past research on acoustic based detection of knee osteoarthritis and other diseases of the knee demonstrate that it is a very important technology for solving this problem. The proliferation of mobile computing combined with the availability of low cost acoustic sensors allows for these detection techniques to be implemented with low cost and practical technology that can have a significant impact on the way knee diseases are diagnosed and treated.

Implementations of acoustic detection in past research have shown good promise for the technology in the field of medicine. In this paper, an approach for characterizing knee health has been proposed based on the STFT and statistical analysis of acoustic signals. The analysis presented here shows promising results on processing techniques for potentially recognizing age based degeneration of knee cartilage. Future work on this subject would require large scale clinical testing that could utilize this work as a guide for what potential biomarkers to look for while trying to identify overall health trends. It is the goal that this work will lead to a better understanding of the acoustic properties and information associated with the human knee and aid diagnosticians detect problems in an easier and safer approach for patients.

REFERENCES