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Development of a Non-Invasive Bio-Acoustics Measurement System for Assessing Articular Cartilage Knee Joint Problem

Anas Mohd Noor*

School of Mechatronic Engineering, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia

*Corresponding author: anasnoor@unimap.edu.my

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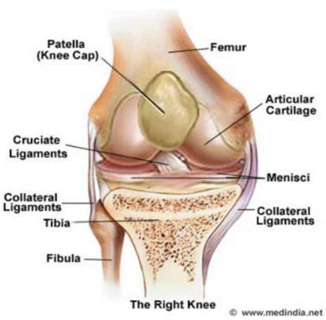
Graphical abstract



Abstract

A technique in measuring and recording of bio-acoustics signals for the assessment of physiological of knee joint articular cartilage conditions has been developed. Currently, invasive technique such as knee arthroscopy and imaging modalities methods are widely been applied in determining problems related to the knee joint. However, these methods are uncomfortable to the patient, performing in static condition, costly instrumentation and maintenance and most of the times it could not reveal the early symptoms of knee articular cartilage problems. Knee acoustical is used to overcome the current practice limitation and could assist physicians to diagnose at the early stage. The measurement system is developed which consists of a high-sensitivity acoustical piezoelectric transducer with frequency response ranges from 2.5 to 5000Hz, the signal conditioning circuit, and real-time signal visualization and analyzed using a short time Fourier transform technique. The knee cartilage produced an acoustic signals are measured non-invasively during a dynamic cycle of flexion-extension and sit-stand-sit movements. This paper also describes the details of hardware components and software used in this system. Six volunteers with normal and injured cartilage involved in this study. The normal conditions of the knee articular cartilage produced a lower frequency component which is less than 120Hz, and abnormal signal shows frequency more than 200Hz is generated. It has been demonstrated that, the developed system prototype could be used to differentiate between normal and abnormal knee articular cartilage acoustic signal using frequency spectral which could be beneficial in the early detection of the problem.

Keywords: Articular cartilage; bio-acoustic; knee joint

Abstrak

Kajian ini menyediakan suatu teknik alternatif didalam pengukuran serta merekodkan isyarat bio-akustik untuk penilaian terhadap fisiologi rawan sendi lutut. Pada masa kini, teknik invasif seperti arto skop dan kaedah pengimejan digunakan secara meluas didalam menentukan masalah artikular rawan sendi lutut. Walau bagaimanapun, kaedah ini adalah kurang selesa terhadap pesakit, dilakukan secara statik, peralatan yang mahal serta penyelengaraanya dan ianya juga tidak dapat mengesan tanda-tanda awal masalah rawan. Bunyi pada lutut digunakan untuk megatasi had praktik semasa dan juga membantu doktor untuk mendapatkan diagnosis pada peringkat awal. Sistem pengukuran yang dibangunkan terdiri daripada tranduser pizoelektrik akustik sensitiviti tinggi yang dengan julat frekuensi dari 2.5 hingga 5000 Hz, litar kondisi isyarat, dan visualisasi isyarat masa-nyata dan dianalisis menggunakan Fourier mengubah masa singkat. Isyarat akustik diukur dari rawan adalah tidak-invasif serta semasa pusingan dinamik untuk lentur-lanjutan dan duduk-berdiri-duduk. Kajian ini juga menunjukkan butir-butir komponen perkakasan dan perisian yang digunakan didalam prototaip ini. Enam sukarelawan dengan rawan lutut yang normal dan cedera terlibat dalam kajian ini. Keadaan normal articular rawan lutut menunjukkan frekuensi yang lebih rendah iaitu di bawah daripada 120 Hz, dan juga menunjukkan isyarat yang tidak normal melebihi daripada 200 Hz. Ini menunjukkan bahawa sistem yang dibangunkan dapat membezakan antara normal dan tidak normal daripada isyarat akustik artikular rawan lutut yang mungkin boleh digunakan didalam pengesanan awal masalah rawan lutut.

Kata kunci: Artikular rawan; bio-akustik; sendi lutut

1.0 INTRODUCTION

The knee joint is the largest and most complex joint structures in the human body. It is surrounded by numerous tendons and ligaments as shown in Figure 1. Tendons are defined as the connection between muscle to muscle and ligaments are connection between bone to bone [1]. Common knee injuries are found to be associated with damage to the articular cartilage or the menisci. The most injuries occur such as chondromalacia patella or known as CMP is identified where the cartilage surface is softens, fibrillate and shed off under the surface of patella and lead to the rough condition [2]. Moreover, ageing is the most factor that contribute to the degradation of cartilage condition.

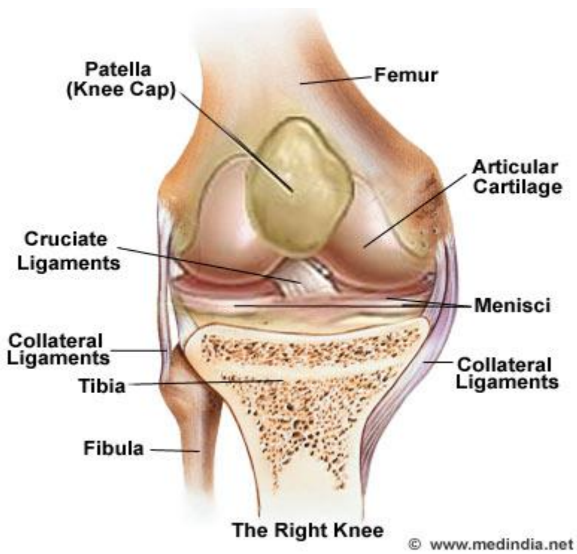


Figure 1 The anatomy of human knee [26]

Currently, an invasive and non-invasive techniques are used for such as knee arthroscopy and imaging modalities such as X-ray, computed tomography (CT), magnetic resonance imaging (MRI) and ultrasonography are widely used for determining articular pathology [3]. Arthroscopy is an invasive technique performed by an orthopedic to look inside the joint using an instrument called the arthroscope. This technique required a patient to be in anesthetic condition where the doctor will view the images thru a small camera inserted to see the anatomy of the knee in detail. Imaging methods are more straights forward where the image of the internal knee is taken and analyzed by the orthopedic. The image shows the condition of knee cartilage and others related joint condition. However, both of these techniques are static, which failed to characterize the functional of the cartilage in terms of softening, stiffness or fissuring that only could be detected and measure during dynamic knee movement [4].However, both methods cannot show the early symptom of knee cartilage problem.

To overcome the limitations of imaging modalities and invasive technique, the acoustic of knee joint has been studied. Back to the 17th century, the claim of first human joint auscultation is created by Robert Hooke where he suggested that the noise of the joint could be used for diagnostic tool. Until the date, there are many studies on this knee acoustical proved that the conditions of normal and abnormal joint could be differentiate [5-7].

Dynamic knee movement such as flexion-extension has been identified as the best knee assessment for joint acoustic analysis. In addition, a sit-stand-sit movement is used to enhance the generated sound because of body weight will provide a load to knee thus producing more articular cartilage friction [8-12]. Acoustical signal generated from this friction is recorded using a transducer and sensor for further signal processing to determine the conditions of knee especially the articular cartilage and menisci. The transducers and sensors applied in their studies such as piezoelectric, optical, accelerometer and acoustic emission sensor are widely used in the assessing of the knee acoustical [13-19]. Meanwhile, various acoustic signal analysis methods have been investigated such as parametric modeling and spectral study [20-22].

In this research, the high-sensitivity bio-acoustic measurement system using computer has been developed to provide a real-time bio-signals measurement from the knee joint to be visualized, recorded and analyzed. Selection of a transducer and signal processing technique would be discussed. This prototype system may could assist physicians in determining the early stage of an articular cartilage problem and provide a non-invasively, cost-effective and rapid detection.

2.0 METHODOLOGY

The complete system compromise of a hardware and software. The hardware consists of an acoustic transducer, signal conditioning circuit and data conversion device. The system software consists of data logging, signal processing, data visualization and graphical user interface. Subjects and details of experiment procedure tested and applied to the system also explained.

2.1 Hardware

2.1.1 Transducer

High sensitive piezo-polymer transducer (MLT1010, AD Instruments) is used to capture the acoustic signal. The piezoelectric element converts mechanical forced (sound-wave) to the transducer active element (polarized material) to generat electrical signal. This transducer has wide ranges of frequency response starting from 2.5Hz to 5000Hz, with a diameter of 2.2 cm and a thickness of 1.2 cm is connected to the signal conditioner circuit using BNC connector type.

2.1.2 Signal Conditioning And Conversion

This hardware consists of two main parts, a filtering circuit and amplification signal. It has been identified that the normal signal of healthy knee acoustic its' range of 0-115Hz, sometime is less than 100Hz [22]. Healthy articular cartilage in a knee produced a lower sound compared to a damaged knee which could generate higher frequency up to several hundred hertz due to its' surface roughness and friction mode. In order to ensure the environment and artifact noise are reduced, filtering at the signal conditioning circuit has been selected using a high-pass filter starting frequency 5Hz using a single pole passive filter. Amplification of signals after filtering is set to be less than 3Vp maximum at the output. The signal will be converted to digital value to be fed to the computer using USB sound card having a single channel 16 bits (ADC) with sample rate of 44.1KHz per second (S/s). The circuit simulation result show that the designed is able to filter signals starting from 10Hz with amplitude of 2.8Vp maximum. Figure 2 shows the design signal conditioning circuit.

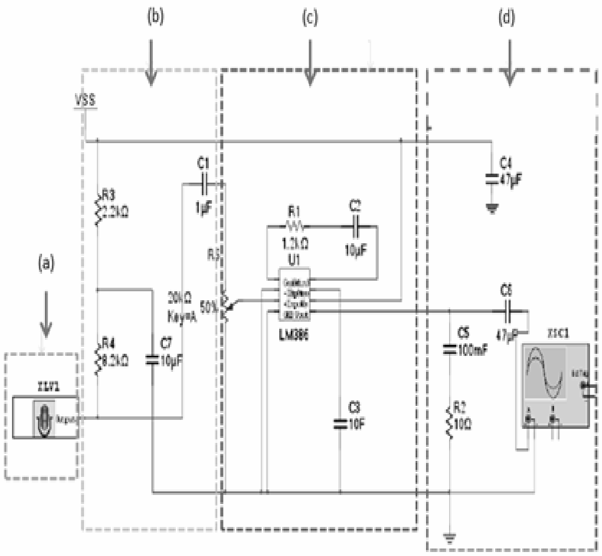


Figure 2 Signal conditioning circuit. (a) Input transducer, (b) Filter circuit, (c) Amplification circuit, (d) Output

2.2 Software

2.2.1 Graphical User Interface

LABView software (Ver. 2012) has been used in this prototype development system. This software will perform frequency analysis and record signals. However, to improve the noise immunity on the measurement system, a digital filter is designed and implemented in this software system using Infinite Impulse response (IIR) Butterworth 4th order band-pass filter. The frequency selected is 10 Hz to 720 Hz which is within knee acoustic ranges.

2.2.2 Signal Processing

Filtered signals are smoothed using the threshold algorithm of wavelet denoising technique. This signal then will be analyzed and visualized using Fourier Transform (FT) and continuous Short Time Fourier Transform (STFT) technique or sometimes known as windowed Fourier Transform. Fourier Transform method commonly used in many applications and it is suitable for periodic signals. However, this technique could not provide frequency components relationship with time which is important to avoid incorrect analysis due to overlapping frequency in FT analysis. STFT is commonly used to analyze non-periodic (time-varying) signals, which could improve disadvantages of Fourier Transform that cannot provide simultaneous time and frequency localization. Therefore, this development system provided both techniques in order to improved knee articular cartilage analysis.

2.3 Subjects

To confirm the consistency of the development system, it should be able to distinguish or show the differences between normal and abnormal articular cartilage conditions. Therefore, six volunteered subjects, ages between 25-30 years old are participating in this experiment. Three subjects, are identified as having a normal healthy knee with no history of a joint problem, and others subjects has been identified to have a history of an injured on the right knee (cartilage damage) within 6 months back.

2.4 Protocol

There are two conditions of experiment performed in this project. As highlighted earlier, the active limbs cycle, flexion-extension of the knee and a sit-stand-sit protocol are claimed by many researchers provide details of the knee acoustics relationship to knee articular cartilage conditions. [23, 24], However, to ensure the signal are measure correctly, the placement of the transducer is important to minimize motion artifacts and increase measurement accuracy. The transducer is placed on the medial compartment and below the mid-line of the patella. It provides good sensitivity because it's the nearest position to the area of the articular cartilage surfaces movement and more stable transducer motion artifacts less affected by skin movement [25]. Figure 3 shows the placement of the transducer on the subject which is the medial meniscus for measuring the meniscus acoustic. A mechanical goniometer also attached to the side of the knee to measure angles during the experiment to ensure motion of subject leg within range angle. Slow warm-up is necessary for keeping the speed of knee flexion and extension constantly before the experiment performed. A goniometer is placed on the knee and tape with a surgical tape. Acoustical measurement is based on the right knee of subjects.

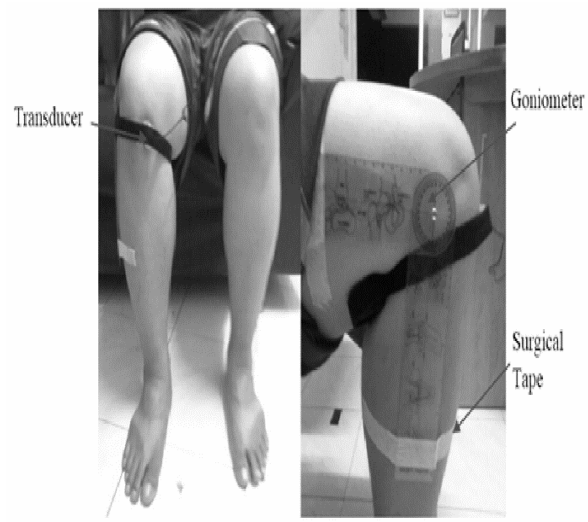


Figure 3 Transducer and goniometer location on the knee

The knee position would be in flexion (90º) and full extension (180º) as during data collection shown in the Figure 4. A cycle consists of 1 extension and 1 flexion. Subjects performed 5 consecutive and repeated active knee flexion and extension movement at constant speed in 10 seconds for 1 cycle from 90° - 180º - 90º in 2 seconds. The subject will repeat this activity three times with 10 minutes rest for each cycle.

Figure 4 Flexion and extension knee movement

The knee position would be to sit (90º) and stand (180º). Subject performed 5 consecutive and repeated active sit-stand-sit movement at constant speed in 10 seconds for 1 cycle from 90° - 180º - 90º in 2 seconds as shown in Figure 5. The subject will repeat this activity three times with 10 minutes rest for each cycle.

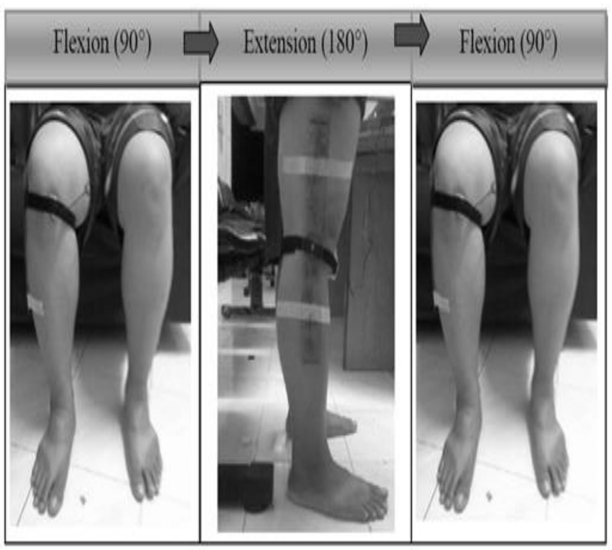


Figure 5 Flexion-extension using sit-stand-sit movement

3.0 RESULTS AND DISCUSSION

Figure 6 shown examples of subject's knee acoustic measured is presented in time-domain signals. The flexion-extension activity in terms of signal amplitude is clearly shown from the graph. A frequency domain analysis using Fourier transform (FT) technique is applied to extract the frequency components of these signals. The ranges of the frequency are between 10Hz – 45Hz with the maximum normalize amplitude are 0.9 as shown in Figure 7. This normal frequency ranges was reported by Hassan M. Bassiouni (2012).

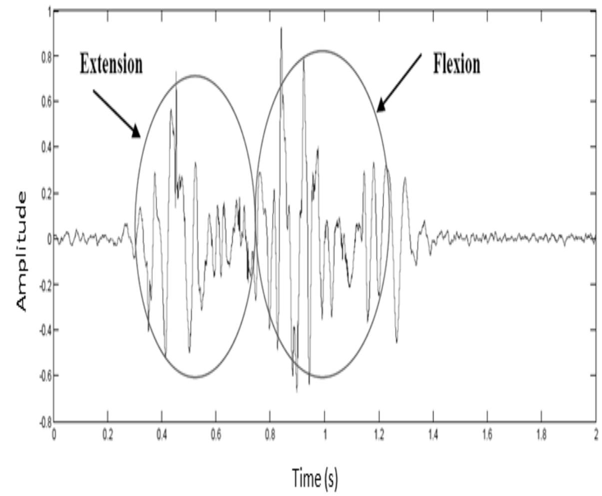


Figure 6 Time-domain signal of healthy subject during flexion-extension movement

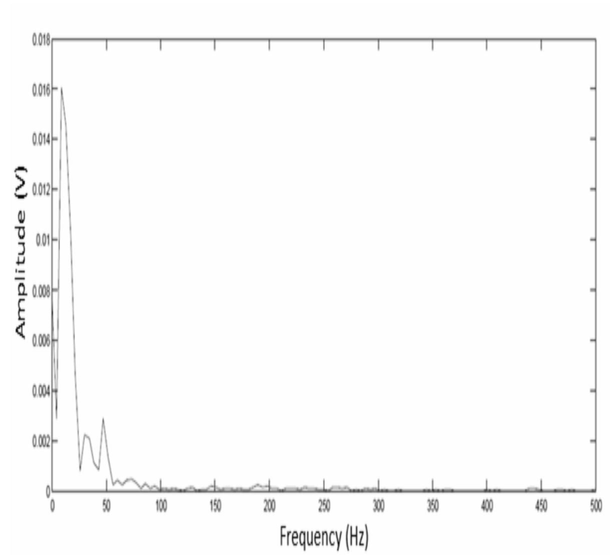


Figure 7 Frequency component signals of healthy subject during flexion-extension movement

Fourier Transform analysis has it limitation to provide time for each calculated frequency. Hence, STFT could elevate this disadvantage, and it is introduced in this system. As shown in the example of a healthy knee articular cartilage in Figure 6. For subjects with damaged articular cartilage to provide higher-frequency components in the range of 0- 200Hz analyzed using both FT and STFT method as shown in an example in Figure 8.

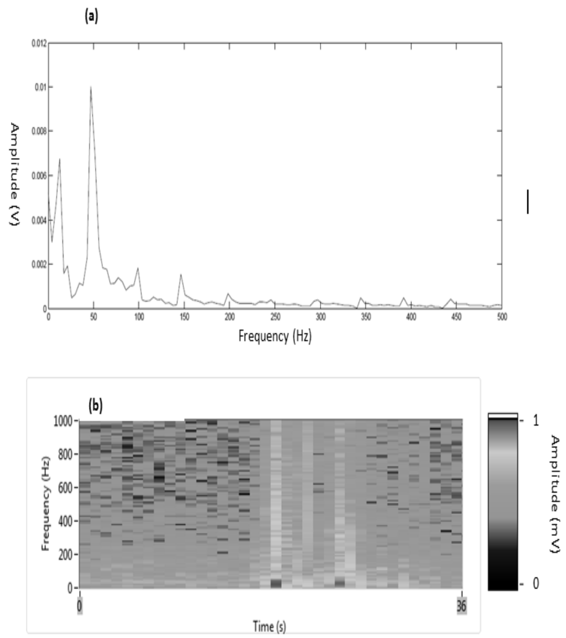


Figure 8 (a) Flexion-extension spectral, (b) Flexion-extension spectrogram

For both the flexion-extension and sit-stand-sit are shown significance differences in frequency component spectra. It also supported the previous claimed that during loading (sit-stand-sit) knee movement, greater force and friction to the articular cartilage which then created a higher frequency compared to the flexion-extension movement without any load. The traumatic cartilage also shows variability between healthy subjects. More frequencies components generated from the traumatic subjects indicated the degeneration of mensci or cartilage. Table 1 show the result based on frequency components on the right knee of the test subjects.

Table 1 Results of bio-acoustic frequency spectra

Subjects	Cartilage conditions	Frequency Average (Hz)	
		Flexion-Extension	**Sit-Stand-Sit**
1	Normal	0-52	0-58
2	Normal	0-48	0- 51
3	Normal	0-50	0- 52
4	Traumatic	0-145	0-152
5	Traumatic	0-160	0-173
6	Traumatic	0-200	0-251

There are many types of diseases regarding cartilage and menisci problem which could be identified based on its special frequency characteristic. Geralf F. *et al.* identified that meniscal tear frequency range is less 320 Hz and degenerated cartilage ranges from 300-600 Hz in their studied. Narender P. *et al.* in their studied identified that Spondyloarthropathy and Rheumatoid arthritis frequency within 100-500 Hz [27]. Another studied by Ippe Matsurra and Masatoshi Naito revealed that osteoarthritis, is around 433 Hz, patellafemoral disorder within 544 Hz and meniscal lesion is about 174 Hz. It can be concluded that degenerated cartilage and mensci shows higher and more frequencies generated due to the developed surface friction.

Higher sensitivity transducer is recommended to improve measurement. The placement of the transducer should be exact under the patella to minimized movement artifact and others noises produced such as muscles and ligaments movement and instrument electrical noise during performing experiments. Some limitations such as circuit filtering frequency where the order of filter is one which affect the critical frequency cut-off. The on-line signal processing sometimes make the system processing is slow due to STFT analyzing.

It also recommended that multi-sensors also could be applied to few different locations use to capture acoustical sound produced and also its signal pattern profiling. It is also suggested that experimental procedure could be enhanced such as adding additional load during flexion-extension movement which will increase stress to the knee.

Additional intelligence processing algorithms for classification to identify a particular knee joint problem by acoustical could improve the measurement system and hence could be used to assist orthopedic to diagnose an early stage of knee arthritis, which is not available by other method. Until today, this field of study is still not yet well understood and analyze due to its' complex dynamic characteristics.

4.0 CONCLUSION

The differences between healthy and unhealthy knee (articular cartilage) conditions could be differentiated using spectral analysis. From the literature, it has been discussed that based on the cartilage and menisci surface conditions, the rough surface would generate more harmonic frequency compared to the smooth surface with less friction which measured by its' acoustical parameter has been proved. With this field of studies, the healthy and unhealthy acoustic frequency characteristics' could be use providing an early information and diagnosis that could not discover by imaging technique.

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