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Design and Verification of Bell-shaped Structure in Negative Pressure Environment for Sound Acquisition of Knee Joint

Yung-Tsung Cheng[1], Cheng-Chi Tai[1], Willy Chou[2], Jiun-Hung Lin[3*]

[1]Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan

[2]Department of Physical Medicine and Rehabilitation, Chi-Mei Medical Center, Tainan, Taiwan

[3]College of Electrical Engineering and Computer Science, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan

*Corresponding author: labview.lin@gmail.com

Abstract

Aging society is currently the common environmental phenomenon in developed countries. The occurrence of chronic diseases is rising with increasing elderly population; degenerative knee arthritis is one of them to feel pain when knees are under load. In addition to detection through doctors' inquiry and palpation, the assistance of medical devices is clinically used for realizing the degree of knee degeneration. However, there is implicit consideration of excessive radiation dose. In order to enhance the operation convenience of knee joint detection and reduce the doubt of safety, digitalization of medical aids is applied to reduce medical staff' burden. A structure different from attached knee auscultation devices is proposed in this study, aiming to effectively reduce friction interference during knee sound measurement. Moreover, a wireless sound and posture detection system with inertial sensor and directional microphone is also proposed to measure body movements and angles through the tiny sound recording function. Meanwhile, wireless transmission function is included to reduce wire connection and enhance wearing comfort during the measurement. The system is completed the prototype design and test; it will be applied to long-term knee health monitoring and clinical preventive healthcare.

Keywords: *rubber capsule, posture detection, knee auscultation, negative pressure, metal sucker*

1. Introduction

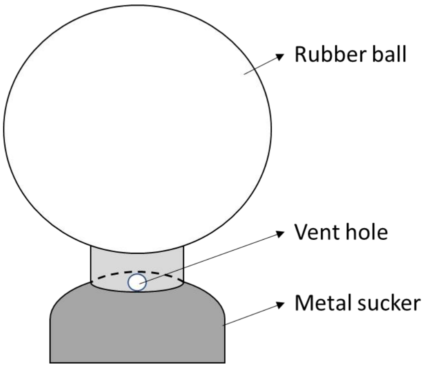
Aging society is currently the common environmental phenomenon encountered in developed countries. Increasing elderly population increases degenerative knee joint diseases. The pain induced by such knee joint diseases would interfere in and affect walking, fall, and even fracture to reduce the quality of daily life and even worsening the conditions [1]. Knee joint lesion detection currently stresses on medical history and physical examination with the assistance of devices to acquire knee information. However, there are doubts of safety for minority groups or specific ethnic groups, e.g. radiotherapeutic instrument check. It would be inconvenient for patients and would result in extra cost burden for health care systems. Auscultation, a physical diagnosis technique through listening to inside sound of an individual, presents the development advantages of low cost and easy operation, compared to X-ray, electrocardiography, ultrasound, magnetic resonance imaging, and computed tomography devices in medical imaging.

Moon et al. [2] used spectrum analysis and level crossing rate (LCR) to classify asthma with sound collected from chest. Chu et al. [3-4] designed an experiment to measure and record sound generated from damaged knee joint and explained that such types of measuring devices could be used for non-invasive evaluation. To achieve such requirements, it was discovered from literature review that it was practicable to recognize injured and healthy knees through knee sound collection [5-9], because the organizational structure of knee joint (skeleton, muscle) would change sound signals of knee joint activity due to deformation. Articles analyzing sound signals as the evaluation and diagnosis basis for improvement are published in past years, e.g. electronic stethoscopes being used for knee auscultation measurement and analysis [10-17] and knee stretching experiments through sitting position [18-19]. People therefore started to enhance the acceptance of non-invasive knee diagnosis systems and techniques. Specifically speaking, such research explained the possibility to recognize injured and healthy knee joint through the frequency characteristics of knee joint sound. Nevertheless, electronic auscultation in most research was handheld or tied to contact knees that friction sound would appear between skin and diaphragm when contacting auscultation diaphragm with knees. The monitoring signals therefore would be easily affected by noise to further influence signal interpretation and analysis. To improve such a problem, an innovative knee auscultation device structure is proposed in this study. The design idea is to install a microphone device, e.g. microphone, above a compressible and flexible rubber suction ball. With the principle of negative pressure, the rubber suction ball is squeezed to suck on the skin surface. Such a design aims to have the microphone device not directly contact the skin and collect sound in the rubber suction ball to remove unnecessary noise interference. Knee lifting posture measurement is also included to provide knee joint activity related information as well as observe the relations between degenerative knee joint sound and stretching angles by corresponding to knee activity sound and the stretching angles. Bluetooth technology is further combined to transmit knee sound and posture signals to the computer end for recording, analyzing, and observing the corresponding relationship. Finally, the system provides a convenient measurement technology, low interference, and real-time integrated knee sound signal analysis platform for clinical researchers acquiring sound diagnosis information.

2. Principle and structure

2.1. Innovative Adsorption Auscultation Device

A rubber suction ball sound-capture device is proposed in this study. The idea of the device comes from the suction ball of electrocardiography lead wire in general hospitals. It is the combination of a rubber ball and a conductive metal sucker, Figure 1(a). The rubber suction ball is squeezed to discharge air inside the ball and then the conductive metal sucker is attached to the skin. The rubber suction ball is then released to have the ball slowly inflate. According to negative pressure, the conductive metal sucker would then suck on the skin, Figure 1(b).

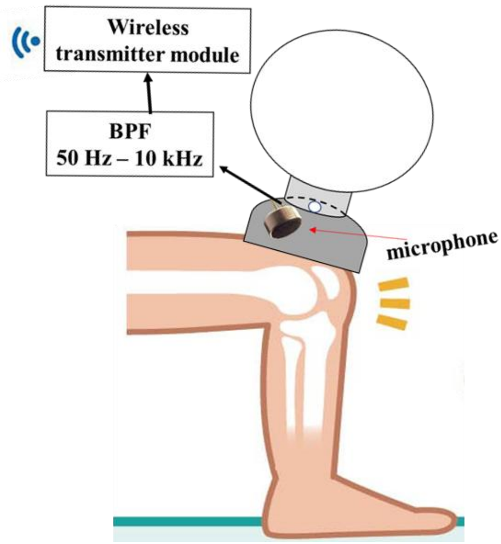


(a)

(b)

Figure 1. Innovative auscultation device design (a) internal structure of device (b) sketch of device adsorbing on skin.

Regarding the sound capture device, a condenser microphone is installed inside the conductive metal sucker, Figure 2. The signal line of the microphone goes through the copper material, which is sealed with silicone to avoid the leakage of sucker. The figure shows that the inside microphone does not contact the skin that the friction effect would not appear during the measurement. Finally, the microphone, after preprocessing, transmits sound through wireless transmission module to the computer end for analysis. The information of the innovative auscultation device shows the length x width x height 2.1 x 2.1 x 4.2cm.



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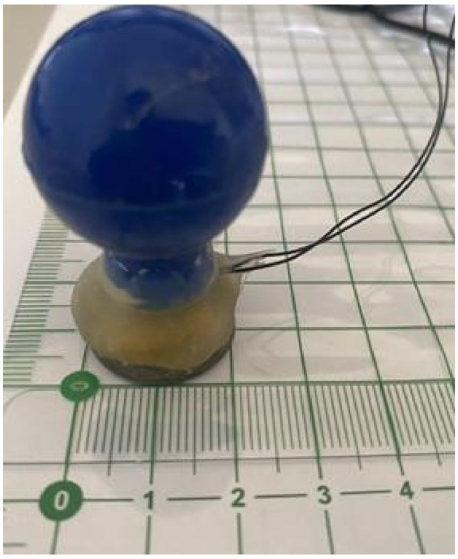


(b)

Figure 2. (a) Sketch of microphone transmission in the innovative structure (b) picture of the innovative auscultation device.

2.2. Wireless acquisition device design

This system presents two major functions on the measurement, including wireless knee sound capture device and wireless knee posture measurement device. First, regarding the wireless knee sound capture device, as described in Section 2.1, a directional condenser microphone is used for recording knee joint sound signals. A wireless sound transmission processor, with the sampling frequency up to 48 kHz without compressing the sound for transmission, is used for the device. The sampling rate is set 44.1 kHz in this study, which could completely transmit knee joint sound signals to the computer end for signal processing and analysis. LabVIEW (National Instruments, NI) is utilized in this study for the interface design on the computer end, Figure 3. Second, the wireless knee posture measurement device mainly acquires calf extension and flexion angles and swing angular velocity signals. The posture sensing device is used for acquiring the calf motion data, which are processed with a microcontroller in a 32-bit ARM Cortex-M4 structure of ST Microelectronics company; the posture sensing data are further transmitted to the computer end through Bluetooth module for angle conversion, observation, and storage, Figure 3(a).

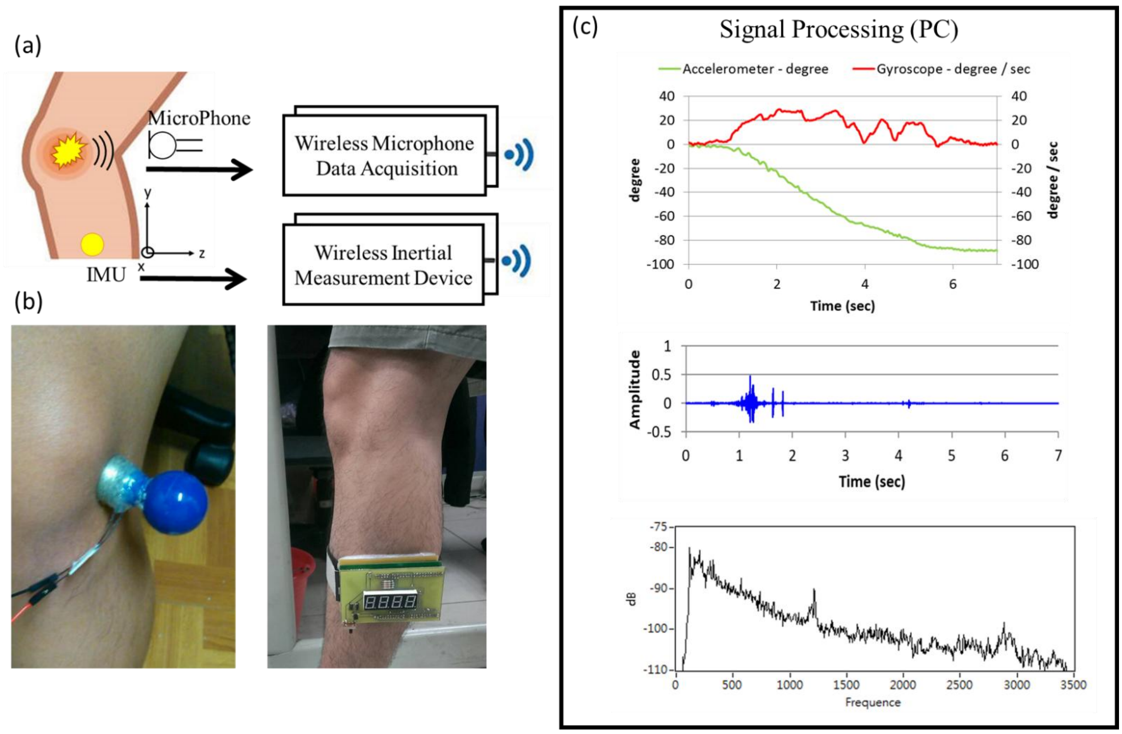


Figure 3. System architecture (a) sketch of wireless sound and posture transmission (b) actual measurement (c) wireless real-time knee joint signal collection interface design. The upper picture displays the time change of calf lifting speed, the middle left is the angle change of calf lifting, the middle right shows the real-time measurement of knee sound wave, and the lower picture displays the spectrum analysis of knee sound wave.

The design through LabVIEW could completely realize the required recording and analysis interface on the computer end. In the signal collection interface, the calf extension/flexion motion signals and knee joint sound could be simultaneously collected, Figure 3(c). The subjects could control the calf lifting speed and angles through the screen, and the measurer could real-time observe the subjects' leg behavior and knee sound waveforms on the computer screen. The system would save the real-time measurement data, with date and time, in TDMS (Technical Document Management System) format and WAV format. The saved data could be used for successive clinical big data statistics and analysis to analyze the degenerative knee arthritis trend.

3. Experiment design

3.1. Verification of adsorption auscultation device

The adsorption auscultation device proposed in this study is verified, Figure 4. The innovative auscultation device and microphone are preceded the same experiment in the process. The anechoic box developed by OE Scientech Co.; Ltd. is used for the test. The noise isolation class (NIC) ≧ 40 could prevent the sound measurement result from ambient noise. The speaker, JS2202AA, with the frequency response 60~20 kHz and distance 15cm, plays 10sec white noise for sound recording. The measured sound signals are converted with computer sound card and analyzed the frequency response through LabVIEW. The results are compared to observe the difference.

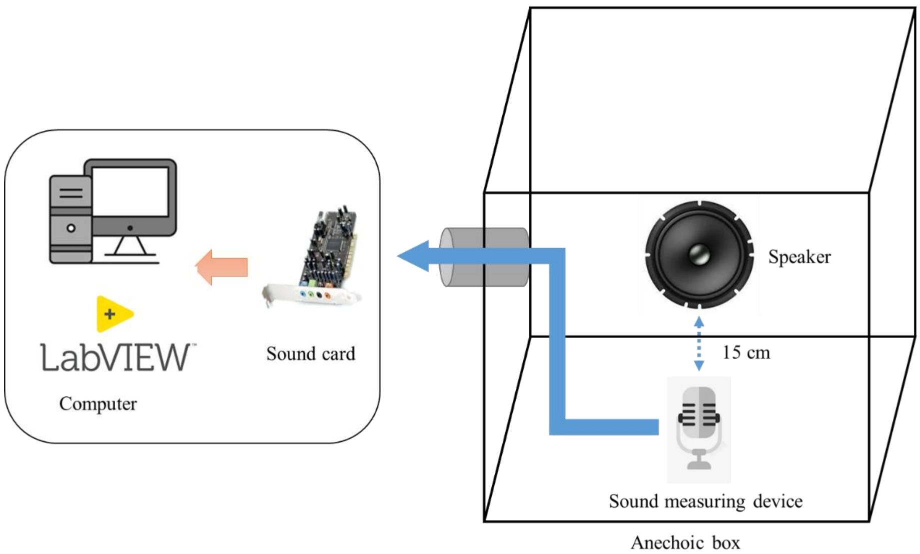


Figure 4. Sketch of adsorption auscultation device experiment

3.2 Experiment of entity knee sound and calf posture measurement

The innovative auscultation device sucking on knee joint is experimented, Figure 5. The wireless acquire device is installed on calf gastrocnemius to acquire sound signals from knee joint extension/flexion as well as the calf swing angles and angular velocity signals. The human machine interface designed in this study is used for analyzing the sound frequency and angles of knee joint and calf activity to observe the effects of speed, movement, and posture angles on knee joint sound during calf extension/flexion as well as to discuss the characteristics and trend. To verify the practicability of the device and the stability of wireless transmission, normal adults aged about 20 are selected for the verification, in order to regulate suitable experiment rhythm and installation comfort.

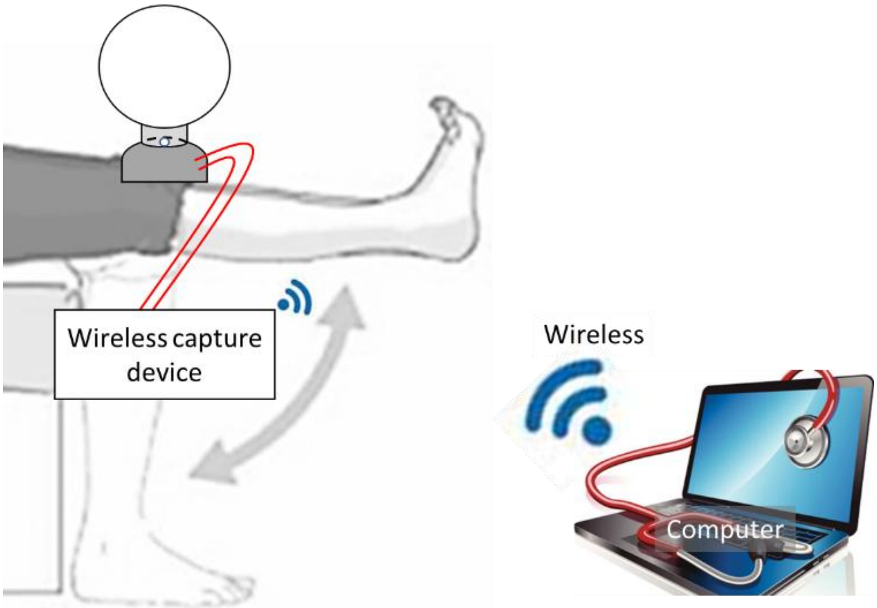


Figure 5. Experiment structure for knee joint sound and calf posture measurement

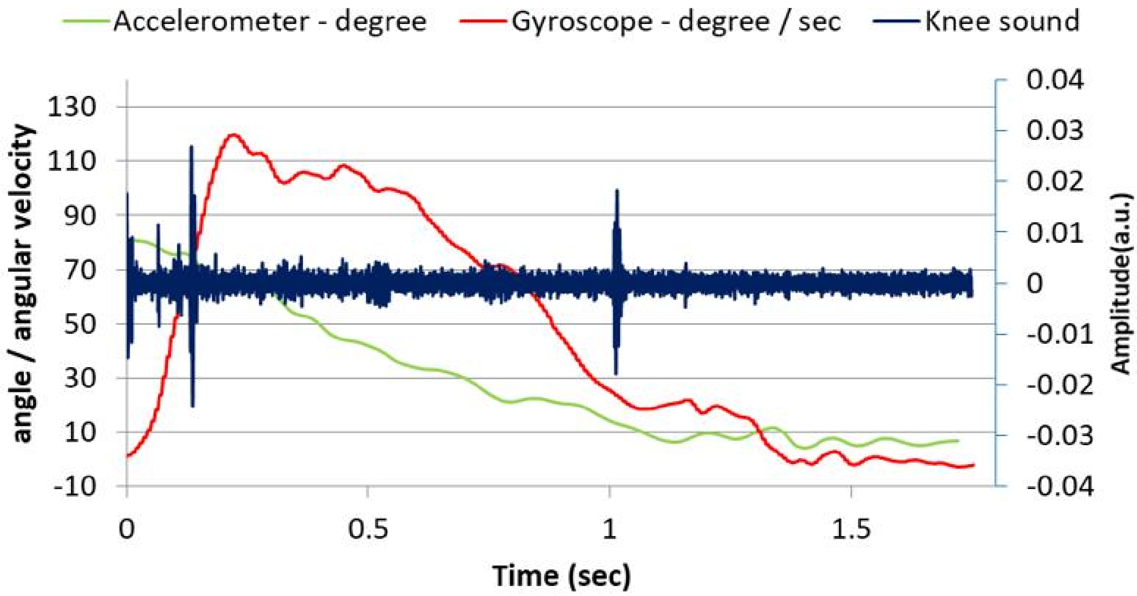
3.3 Experiment of suspected degenerative knee joint disease

To better understand the relations between sound characteristics and posture sensing during knee extension/flexion, the research subjects are patients in rehabilitation area and ward area who are first requested by a doctor and then palpated as possibly degenerative knee arthritis. During the measurement process, the innovative auscultation device is sucked on knee joint and the wireless acquire device is fixed on the calf gastrocnemius. Each subject sits on the chair with both legs relaxed during the experiment. The extension/flexion activity is then preceded. The experiment time is fixed 30sec or 5 swings of extension/flexion movement. The body data collection research is approved through Institutional Review Board of Chi Mei Medical Center.

4. Result

4.1. Experimental results of entity knee sound and calf posture measurement

The measurement results of normal adults' knee sound and calf posture are shown in Figure 6. Figure 6(a) shows the knee joint sound signals during calf lifting, and angle and angular velocity signals reveal that the maximum and minimum angular velocity appears during calf lifting. Self-directed lifting motion is preceded in the process that the subjects' relaxation during lifting would be observed from the measurement data. Furthermore, the sound signals also reveal the calf lifting process, and the related sound signals are captured. Figure 6(b) shows the spectrum analysis result of knee joint sound signals during calf lifting. The above results reveal that sound and posture could be obviously and effectively recorded the data during the calf lifting experiment. The data change also clearly reveals no other problems in the correspondent data that the verification of the data measurement and recording is practicable.



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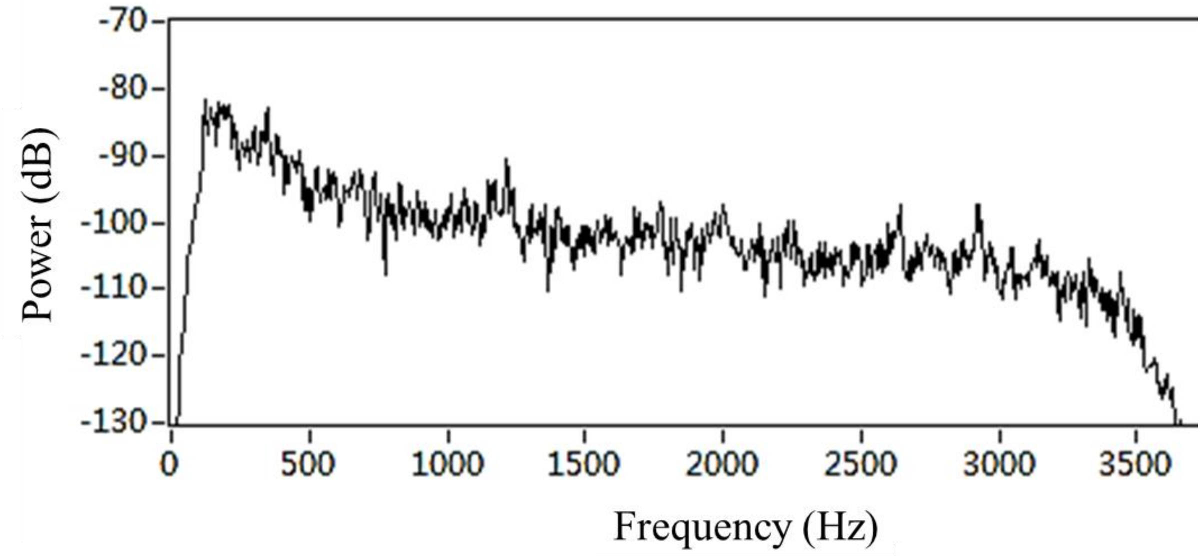
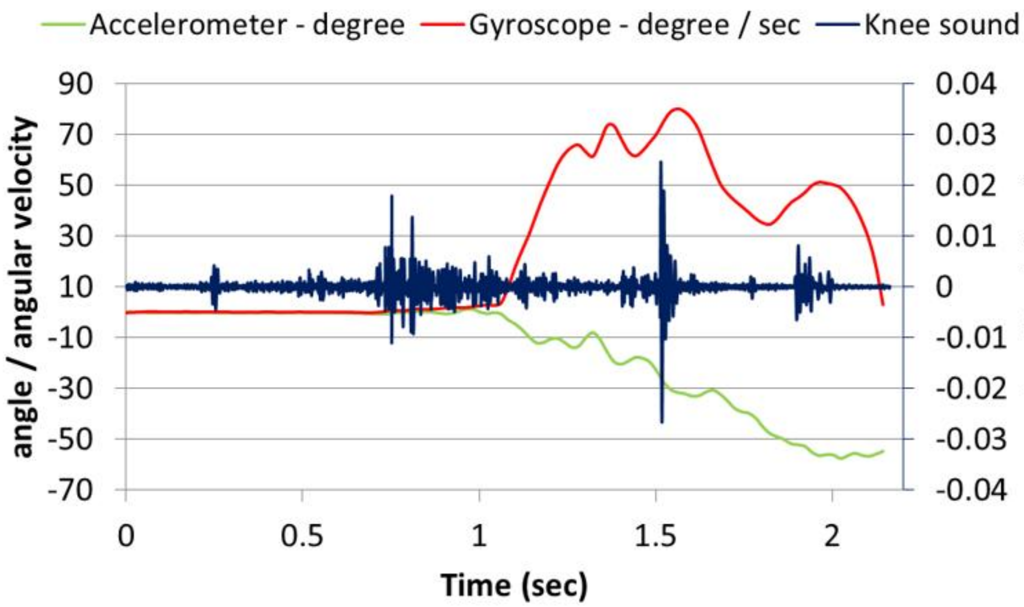


(b)

Figure 6. Normal calf posture measurement and knee sound of calf lifting experiment (a) angle、angular velocity signals and sound signals (b) spectrum analysis

4.2. Experiment of suspected degenerative knee joint disease

The following experimental result is a middle-aged woman with normal legs being able to self-control calf lifting. The subject is slightly plumply but is suspected as a degenerative knee arthritis patient through clinical doctor's palpation. Figure 7 shows the angle and angular velocity signals and sound signals of the subject's left leg lifting as well as the spectrum analysis result. The entire knee joint activity lasts for about 2.2sec. From the angular velocity change in Figure 7(a), it is discovered that the subject is ready for forcing or just about to force the knee joint in the beginning of signal rise/drop, and shows obvious sound signals in the time interval of 0.6-0.7sec and at 1.5sec. The spectrum analysis curve, Figure 7(b), reveals stronger energy on low frequency (100 Hz ~ 400 Hz) and high frequency (1,200 Hz ~ 1,700 Hz).



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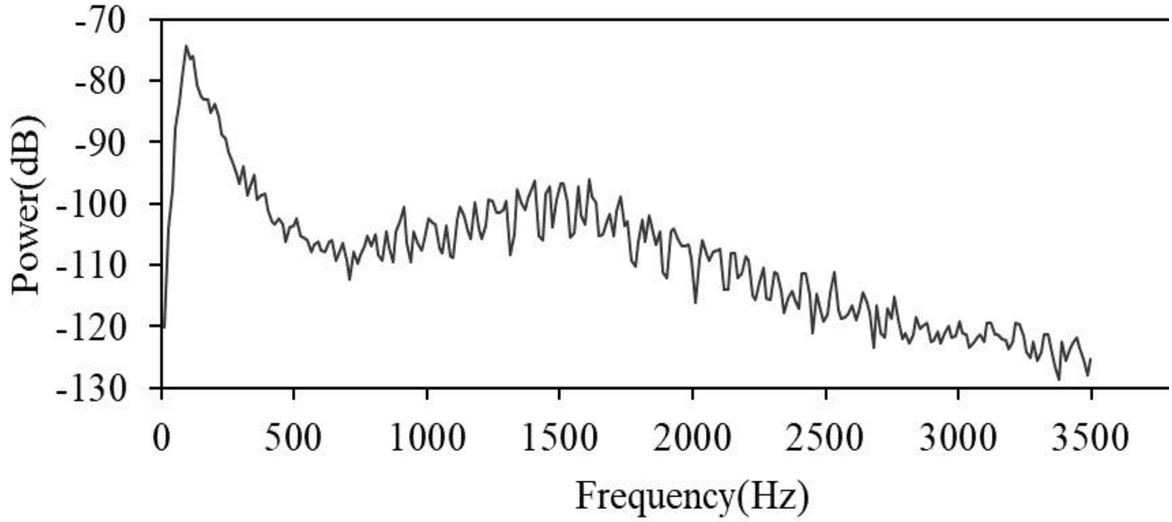

(b)

Figure 7. Left leg lifting and sound data of patients with suspected degenerative knee arthritis (a) angle、angular velocity signals and sound signals (b) spectrum analysis

5. Discussion

The design and verification of bell-shaped structure in negative pressure environment for sound acquisition of knee joint system are preliminarily completed in this study. The verification result of the adsorption auscultation device shows that knee sound source is regarded as a speaker, the adsorption auscultation device developed in this study is regarded as a sound collector to focus knee sound, through sound reflect/refraction principles, and enhance sound strength. The directional microphone in the sound collector could collect knee joint sound as well as isolate external ambient noise. In comparison with general microphones, the signal results present outstanding signal strength in low frequency, and the signal strength trend in medium high frequency appears about the same as general microphones. Apparently, the adsorption auscultation device presents significant effects on the experiment result. Regarding the verification of entity knee sound and calf posture measurement, Figure. 6 reveals that knee joint would appear sound when the calf is lifted and put down without exceeding the range before 45°. The spectrum analysis result shows the frequency range and the knee activity sound range in literature in 200 Hz ~ 3,500 Hz, where the stronger energy distributes in low frequency (200 Hz ~ 500 Hz) and high frequency (1000 Hz ~ 2000 Hz). It is considered reasonable according to current signal analysis results.

Another key experiment is the suspected degenerative knee joint disease experiment test in the hospital to discuss whether the system could enhance clinical medical diagnosis. The analyzed data are close to the degenerative knee arthritis characteristics described in literature [20], and the spectrum analysis result also appears low frequency and high frequency points with larger energy. The subject, under normal swing, shows two frequency intervals with larger energy in the spectrum analysis, including low frequency interval 100 Hz ~ 400 Hz and high frequency interval 1000 Hz ~ 1700 Hz. As shown in Figure 7, the data analysis results are close to the knee joint problems on doctor's palpation diagnosis. In other words, the correct result of a suspected degenerative knee arthritis disease should be judged by doctors with currently accepted diagnosis tool, X-Ray, to achieve the accurate verification.

6. Conclusion

To discuss the innovative knee auscultation device and the extension/flexion posture angle and sound judgment and analysis of knee joint extension/flexion posture activity, an electronic wireless stethoscope with the function of posture and adsorption auscultation is developed in this study. The system presents handiness, wireless transmission of measurement data, and real-time measurement, analysis, and recording in long period. The measurement experiment with the innovative knee auscultation device could observe the signal difference between degenerative knee arthritis patients and normal knee joint. Furthermore, calf posture signals are recorded for analysis. Such data could provide reference for clinical doctors' diagnosis. The experiment results in this study match the trend in past literature. When the indicative parameters of degenerative group, e.g. degeneration level, seriousness, and posture, are quantified as the variables, it would effectively enhance the judgment of conditions. The system could be used for long-term knee health monitoring as well as data collection and comparison to build a complete signal database for clinical preventive healthcare.

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