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# Implementation of Wireless Knee Auscultation System Using Innovative Suction Device

Yung-Tsung Cheng,[1] Jiun-Hung Lin,[2*] Huai-Wei Lin,[3]
Willy Chou,[4] and Cheng-Chi Tai[1**]

[1]Department of Electrical Engineering, National Cheng Kung University,
No. 1, University Road, Tainan 70101, Taiwan
[2]College of Electrical Engineering and Computer Science,
National Kaohsiung University of Science and Technology,
No. 1, Daxue Rd., Yanchao Dist., Kaohsiung 824005, Taiwan
[3]Department of Electronic Engineering, Kun Shan University,
No. 195, Kunda Rd., Yongkang Dist., Tainan 71003, Taiwan
[4]Department of Physical Medicine and Rehabilitation, Chi-Mei Medical Center,
No. 901, Zhonghua Rd. Yongkang Dist., Tainan 71004, Taiwan

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Most developed countries now have aging societies, and the associated increases in the elderly population have led to an increase in the prevalence of chronic diseases. Degenerative knee arthritis is one such disease, in which pain is experienced when the knee is moved. Knee joint degeneration is detected using technological methods in addition to consultation and palpation by a doctor. Clinically, the degree of knee injury is often determined with the aid of radiological medical equipment, but these have safety considerations such as excessive radiation doses. The desire to improve the convenience of operating on the knee joint and reduce safety concerns has prompted the digitization of medical aids, which can decrease the burden on doctors and other medical professionals. In this paper, we propose an innovative knee auscultation device that is designed to reduce noise due to friction when measuring knee sounds. A wireless sound and posture detection system has also been constructed with inertial sensors and directional microphones. The system can simultaneously record low-intensity knee sounds and knee flexion angles. To improve the wearing comfort during measurement, wireless transmission technology is used to reduce wired connections. The prototype design and testing of the system have been completed, and the system could be used for long-term knee health monitoring and clinical preventive medicine in the future.

## 1. Introduction

Aging societies are now common in developed countries. The associated increase in the elderly population has increased the prevalence of degenerative knee joint disorders, which cause pain that interferes with walking and reduces the quality of life.[(1)] Obtaining the medical

[*]Corresponding author: e-mail: labview.lin@gmail.com
[**]Corresponding author: e-mail: ctai@mail.ncku.edu.tw
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history and conducting a physical examination have been crucial in assessing knee joint pathology. However, there are limitations in performing radiological examinations in specific groups owing to safety concerns. Auscultation is a physical diagnostic technique that listens to sounds produced within the body. This is more economical, simple, and convenient for initial diagnoses than other imaging techniques such as X-rays, electrocardiograms, ultrasonography, magnetic resonance imaging, and computed tomography.

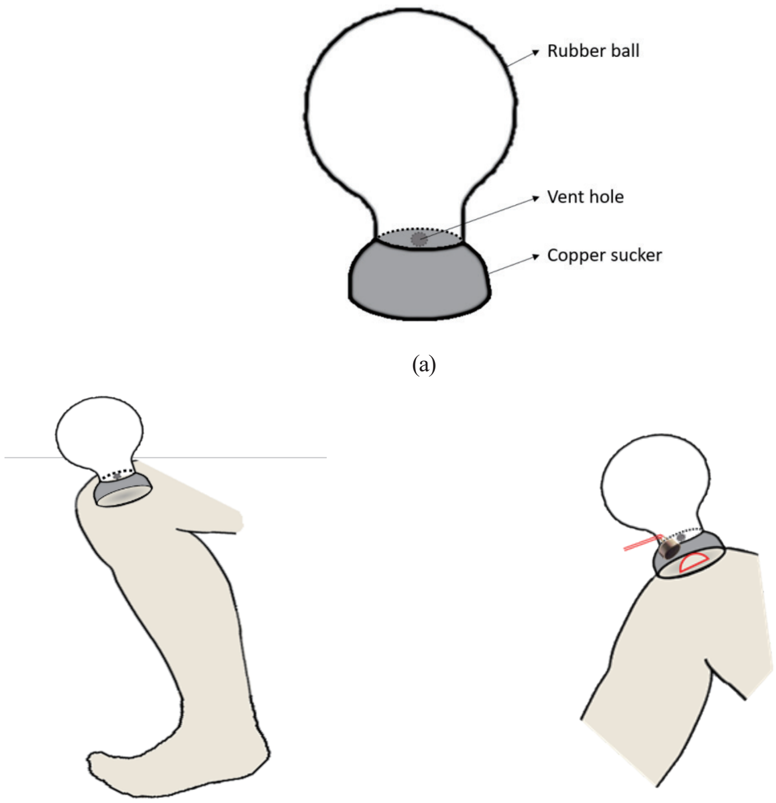
Moon *et al.*[(2)] characterized asthmatic sounds recorded from the chest via spectral analysis and the level crossing rate. Similarly, Chu *et al.*[(3,4)] designed noninvasive methods for measuring and recording sounds produced by an injured knee. Injured knees can be distinguished from healthy knees by recording the sounds that they produce,[(5–9)] since these sounds are affected by the structures of the bony and muscular tissues. Recently reported improved diagnostic techniques based on the analysis of these sound have facilitated the measurement and analysis of joint auscultation using electronic stethoscopes.[(10–17)] as well as knee extension and flexion experiments performed in a seated position.[(18,19)] Noninvasive knee diagnostic systems and technologies are progressively being employed to distinguish between injured and healthy knee joints by characterizing the spectra of knee joint sounds. Handheld devices and those externally attached to the knee are widely adopted for electronic auscultation, but the characteristics of the friction between the skin and the auscultation membrane surface affect the analysis of the signals recorded by such devices.

To address this limitation, we propose an innovative design in which a microphone is installed on a compressible and elastically recoverable rubber capsule in a knee auscultation device. The rubber capsule is attached to the skin surface using negative pressure, which eliminates noise in the recorded sounds associated with a microphone being in direct contact with the skin. Additionally, we have used a computer to record, analyze, and establish the relationship between recorded sounds and posture signals of the knee transmitted via Bluetooth wireless technology during knee motions. This novel system enables clinical researchers to obtain complete diagnostic information via a convenient real-time integrated knee sound signal measurement and analysis platform operating in low-interference conditions.

## 2. Principles and Design

### 2.1 Innovative auscultation device

In this research, we recorded body sounds using a rubber-capped copper sucker composed of rubber and conductive copper that works in a similar manner to the electrocardiogram lead suction ball that is widely used in general hospitals. The copper sucker comprises two parts, as shown in Fig. 1(a). During its operation, part of the air in the ball is removed via the vent hole by squeezing the rubber suction ball, which tightly holds the conductive copper sucker after attaching it to the skin by negative pressure, as shown in Fig. 1(b), and then loosening the rubber suction ball. When the copper cup adsorbs on the skin, the skin covered in the copper cup would be uplifted due to negative pressure adsorption, as the red area in Fig. 1(c).




(a)

(b) (c)

Fig. 1. (Color online) Design of the innovative auscultation device: (a) internal structure of the device, (b) schematic of the device attached to the skin, and (c) skin adsorbed in the device

A sound recording device based on a condenser microphone was placed in the conductive copper suction cup. Figure 2 shows the signal wire of the microphone passing through the copper material to the outside. Silicone was packed around the wire to prevent air leaks from the suction cup. Additionally, the internal microphone is not in contact with the skin so as to avoid noise due to friction. The microphone signal is preprocessed and then transmitted to the computer via the audio wireless transmission module for analysis. The real device information shows the length × width × height of the innovative auscultation device and wireless capturing device, 2.1 × 2.1 × 4.2 cm$^3$, in Fig. 2(b), and 6.5 × 9.7 × 2.8 cm$^3$, in Fig. 2(c), respectively.

## 2.2 Design of the wireless capture devices

The system comprises two wireless devices: one for recording knee sounds and the other for measuring the knee posture. The first device uses a directional condenser microphone for recording knee joint sound signals, as described in Sect. 2.1. This device uses a wireless sound transmission processor operating at a sampling frequency ≤48 kHz, and transmits uncompressed

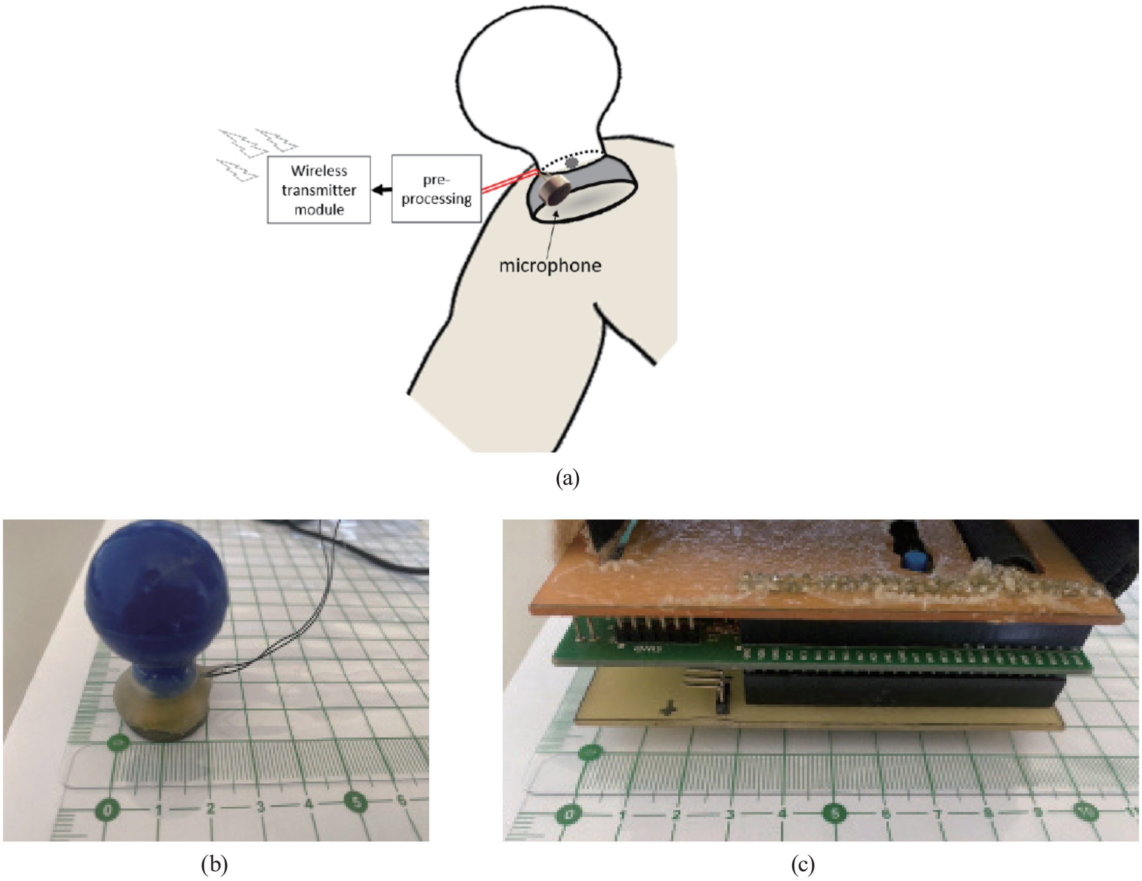



Fig. 2. (Color online) (a) Schematic of the microphone transmission method in the innovative device, (b) real innovative auscultation device, and (c) wireless capturing device.

signals. In this study, we set the sampling rate to 44.1 kHz, which was sufficient to transmit the captured knee joint sound signals to the computer for signal processing and analysis, and used LabVIEW graphic control software (National Instruments) to design the interface on the computer, as shown in the upper transferring path of Fig. 3. The second device is mainly used to capture the signals associated with the extension and flexion angles of the calf as well as the angular velocity of the leg swing. We use a posture sensing device, which is an inertial measurement unit (IMU) integrating an accelerometer and a gyroscope sensor, for measuring the rotational angular velocity and linear acceleration of an object in 3D space. The angular velocity and acceleration signals captured by the above two sensors are processed to calculate the actual motion state of the object. They are also used for calculating the precision placement of posture, aiming to measure and record the swing motion data of calves so that researchers or physicians in hospitals could measure the data for successive analyses to obtain the calf movement data, while the posture is sensed by a Bluetooth module after processing with a 32-bit ARM Cortex-M4 microcontroller (ST Microelectronics). The data are transmitted to the computer for angle conversion, observations, and storage, as shown in the lower transferring path of Fig. 3.


Fig. 3. (Color online) Schematic of wireless knee sound and posture data transmission.

Figure 4 shows the signal recording interface that can simultaneously display the movement signals and knee joint sounds during calf stretching. The subject can adjust and control the speed and angle of the calf extension/flexion through the interface, and the measurement personnel can monitor the leg behavior and knee sound waveforms of the subject on the computer screen in real time. The system saves the real-time-measured data of the subject in a technical document management system in WAV audio file formats, with the date and time used to produce file names. Big-data statistical analysis can be applied to the stored data to determine whether degenerative knee arthritis is present, and any trends therein.

## 3. Experiments

### 3.1 Verification of the attached auscultation device

Figure 5 shows an experimental verification method for the proposed attached auscultation device. The same experiment will be performed with the innovative auscultation device and microphone during the experimental verification process. The experimental setup was developed by Ou Yi Technology. A soundproof box rated to noise isolation class ≥40 is used to prevent environmental noise from affecting the sound measurements. The speaker (model JS2202AA) playback sound length for voice recording is 10 s of white noise. The speaker frequency response is 60–20 kHz, and the distance to the speaker is 15 cm. The measured sound signal is sampled using a computer sound card, and its frequency spectrum is determined using LabVIEW. The results are compared to detect differences between the two wireless devices.

### 3.2 Validation experiment of measurements of physical knee sounds and calf posture

As shown in Fig. 6, the wireless capture device is installed on the calf muscle to record the sound signal generated by the knee joint when it is extended/flexed, and also the signals of the angle and angular velocity of the calf swing. The human–machine interface designed in this research is used to analyze the spectrum of the sound and the angular motion of the knee joint and calf during movements, to determine how the speed and posture angle influence the knee joint sounds when the calf is raised and lowered. To verify the usability of the device and the stability of wireless transmission, an experiment was first performed on a healthy adult aged 20 years to calibrate the experimental rhythm and installation comfort.

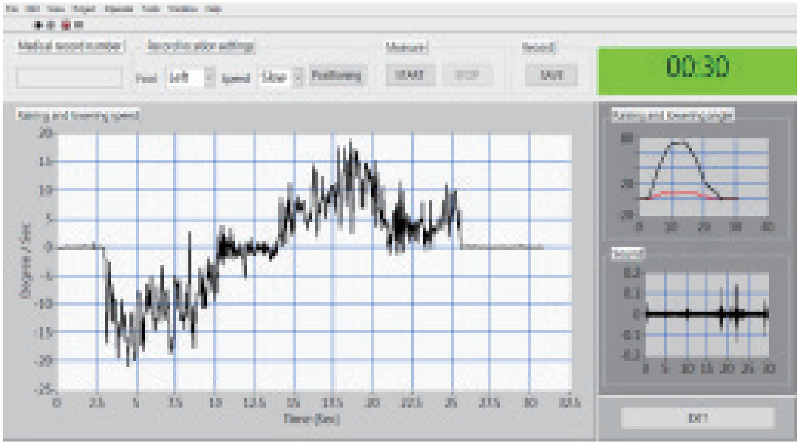



Fig. 4. (Color online) Interface of the wireless real-time knee joint signal recording device. The left graph displays changes in calf extension speed over time, the upper-right graph displays changes in the calf extension angle, and the lower-right graph displays the real-time-measured knee sounds.

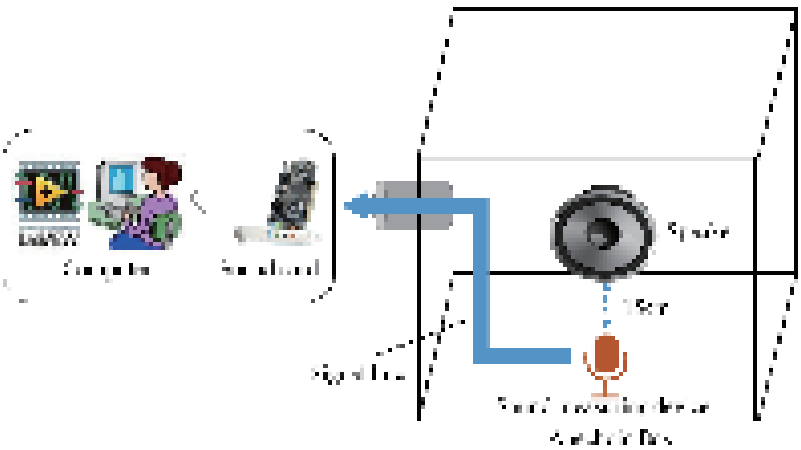


Fig. 5. (Color online) Schematic of an experiment using the attached auscultation device.


Fig. 6. (Color online) Experimental framework of knee joint sound and calf posture measurements.

### 3.3 Experiments on suspected degenerative knee joint diseases

To gain a deeper understanding of the relationship between the characteristics of sound produced during knee extension/flexion and the sensed posture, a doctor identified patients in rehabilitation and general wards with degenerative knee arthritis through palpation. We attached our innovative auscultation device to the knee joint, and the wireless capture device was fixed to the calf gastrocnemius muscle during the experimental measurements. Each subject sat in a relaxed manner on a chair while performing knee extension/flexion. The duration of each experiment was either up to 30 s or when five sets of extension and flexion movements had been performed. The human body data collection research was approved by the human test review committee of Chi Mei Hospital.

## 4. Results and Discussion

### 4.1 Verification of the auscultation device

The results of the experiment for testing the microphone frequency response are shown in Fig. 7. The spectra recorded by the microphone showed that the sound reception of the innovative auscultation device was more prominent than that of the microphone alone between 100 and 500 Hz, while the performance between 1800 and 3500 Hz was equivalent to that of the microphone. For the performance between 500 and 1800 Hz, although the signal from the innovative auscultation device slowly attenuates, the overall trend indicates that it still follows the curve of the microphone in its changes, and so it was concluded that reliable recordings could be obtained from the microphone inside the auscultation device.

### 4.2 Validation test results for physical knee sounds and calf posture measurements

The results of the verification experiments for measuring knee sounds and the calf posture in healthy subjects are shown in Fig. 8. According to the angle and angular velocity signals in

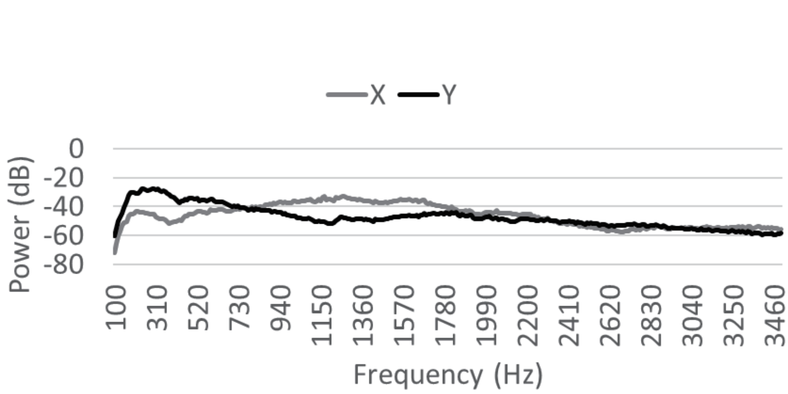
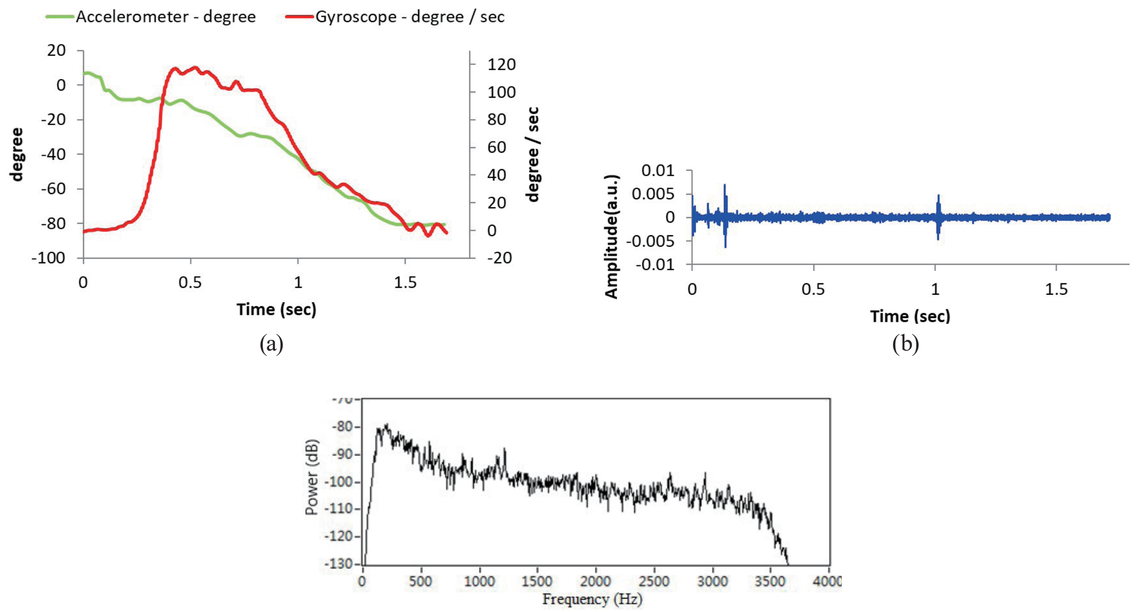



Fig. 7. Verification of microphone recordings (*X* represents the microphone alone, *Y* represents the microphone inside the innovative auscultation device proposed in this research).




(c)

Fig. 8. (Color online) Normal calf posture measurements and knee sounds during calf raising/lowering tests: (a) angle and angular velocity signals, (b) sound signals, and (c) the calculated spectrum of the knee joint sounds.

Fig. 8(a), the maximum and minimum angular velocities both occurred during calf extension/flexion. Figure 8(b) shows the sound signal of the knee joint when the calf was extended/flexed. The actual extension/flexion process involves an autonomous lifting movement, and the subject relaxing slightly during the extension/flexion process will be observed in both the measured data and the sound signal. During the process of calf extension/flexion, the relevant sound signals are indeed captured. Figure 8(c) shows the spectrum of the knee joint sound signals during calf extension/flexion. The complete sound and posture data can be clearly and effectively recorded via the calf extension/flexion experiment. Additionally, changes in the data are clearly evident, and no inconsistencies in the data were detected, indicating that the recorded measurement data are reliable.

### 4.3 Experiment on suspected degenerative knee joint disease

A middle-aged female with a relatively plump body type, healthy feet, and who was able to lift her calf on her own was diagnosed via palpation by a doctor with suspected degenerative knee arthritis. Figure 9 shows the angle and angular velocity signal data and sound signals recorded at the subject’s left foot, and the corresponding spectrum of the knee joint sounds. The knee joint activity was recorded for about 1 s. Changes in the angular velocity can be seen in Fig. 9(a). The early stage of the signal rising or falling corresponds to the subject preparing to apply force to the knee joint or just beginning to apply force. As shown in Fig. 9(b), prominent sound signals were recorded from 0.2 to 0.3 s and at 0.6 s. The spectrum in Fig. 9(c) shows a rapid reduction in power from 200 to 500 Hz and from 1100 to 1600 Hz.

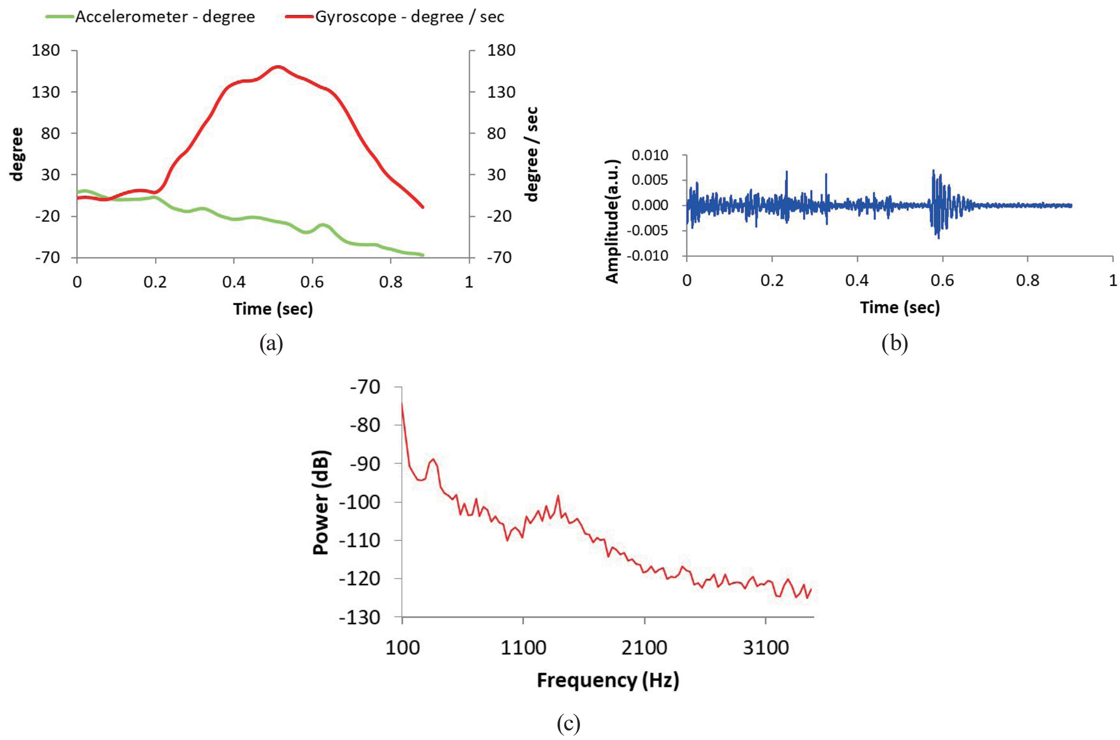



Fig. 9. (Color online) Left calf posture measurements and knee sounds in a patient with suspected degenerative knee arthritis: (a) angle and angular velocity signals, (b) sound signals, and (c) the spectrum of the knee joint sounds.

## 4.4 Discussion

In this study we designed and analyzed a wireless auscultation and posture detection system for the knee. The wireless auscultation device developed in this study records sounds during knee movements using the principle of sound reflection and refraction. The use of a directional microphone inside a cover isolates it from external environmental noise and amplifies the recorded knee sounds. The obtained signals are comparable to those recorded using the microphone alone at low frequencies, while in the middle- and high-frequency bands, the trend of the signal strength is similar to that of the microphone alone. These results indicate that the design of the wireless auscultation device avoids noise due to friction.

The physical knee sounds and calf posture detection experiments showed that the frequency spectrum of the knee joint sounds did not exceed beyond 200–3500 Hz when the calf was extended or flexed up to 45° (Fig. 8), which is consistent with reports in the literature. The power level was highest at 200–500 Hz and 1000–2000 Hz.

Another experiment was performed to test if the novel system can be used to clinically diagnose suspected degenerative knee joint disease. The features of degenerative knee arthritis derived from the data analysis were similar to those described in the literature,[20] and the spectrum also exhibited two high-energy low-frequency and high-frequency regions, at 200–500 Hz and 1000–1500 Hz, as shown in Fig. 9. The primary results of the data analysis were very similar to those obtained in palpation diagnoses of patients with degenerative knee arthritis. However, the doctor would still need to perform X-ray investigations to verify a diagnosis of degenerative arthritis.

## 5. Conclusions

To explore the usefulness of an innovative knee auscultation device in diagnosing patients with degenerative knee arthritis, we analyzed the relationship of the posture angle with the sound generated by the knee joint during extension and flexion activities. In this research, we developed a system that can be considered to be an electronic wireless stethoscope with posture and auscultation functions. This system is portable and allows wireless transmission of measurement data, real-time measurements, analysis, and long-time recording.

In this study, we designed an innovative knee auscultation device for differentiating between patients with degenerative knee arthritis and healthy knee joints based on their characteristic signals. Angle measurement is added in the experiment as the articular cartilage in osteoarthritis is worn and thinned that the louder friction sound between femur and tibia becomes abnormal crepitation, and obvious difference and pain are felt during bending-angle motion. For these reasons, the relationship between angle sensing and sound, in addition to spectrum and sound, could be used for analyzing symptoms. Meanwhile, it could ensure the complete and accurate extension and flexion activities during patients' measurement experiment, as the reference for clinicians' diagnoses. The experimental results were consistent with the findings of past research. Expressing the relevant index parameters of degraded groups, such as degradation grade, severity, and posture parameters, as quantified variables could effectively improve judgments of disease conditions. In the future, this system could be used to monitor long-term knee health, to collect and compare data for constructing a complete signal database, and contribute to clinical preventive medicine.

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## About the Authors

**Yung-Tsung Cheng** is working toward his Ph.D. degree at the Department of Electrical Engineering, National Cheng Kung University, Tainan City, Taiwan. His research interests are in the areas of biomedical circuits and systems, biomedical signal processing, and biosensors.

**Jiun-Hung Lin** received his B.S. degree from Kun Shan University, Tainan, Taiwan in 1998, and his M.S. degree from I-Shou University, Kaohsiung, Taiwan, in 2000, and his Ph.D. degree from National Yang-Ming University, Taipei, Taiwan, in 2006. From 2006 to 2021, he served as assistant professor and associate professor in the Department of Electronic Engineering, Kunshan University. Since 2021, he has been an associate professor at the National Kaohsiung University of Science and Technology. He is also an associate researcher at Chi Mei Medical Center, Tainan, Taiwan. His research interests are in medical technology aids, adaptive noise cancellation technology, automation control, and system integration. (jhlin001@nkust.edu.tw)

**Huai-Wei Lin** received his B.S. and M.S. degrees from Kun Shan University, Tainan in 2014. His research interests are in biomedical system design and signal processing.

**Willy Chou** received his B.S. degree in medicine from National Taiwan University, Taipei, Taiwan, in 1989, and his M.S. degree in human resource management from National Sun Yat-Sen University, Kaohsiung, Taiwan, in 2003. He is currently an assistant professor with the Department of Leisure Management, Cha Nan Pharmacy & Science University, Taiwan. He is the Director of the Physical Medicine & Rehabilitation Department, Chief of the Human Resource Department, and Secretary of Medical Affairs of Chimei Medical Center, Chimei, Taiwan. His current research interests include biomedical assistive devices and rehabilitation medicine.

**Cheng-Chi Tai** received his B.S. degree from the Department of Electronic Engineering, Chung Yuan Christian University, Taoyuan City, Taiwan, in 1986, his M.S. degree from the Department of Electrical Engineering, National Cheng Kung University, Tainan City, Taiwan. in 1988, and his Ph.D. degree from Iowa State University, Ames, USA, in 1997. From 1990 to 1992, he was an assistant professor at Kun Shan University, Tainan City, Taiwan. From 1990 to 1992, he was an assistant professor at Kun Shan University, Tainan City, Taiwan. Since 1997, he has been a professor at the Department of Electrical Engineering, National Cheng Kung University, Tainan City, Taiwan. His research interests are in bio-electronic instrumentation system, electromagnetic, pulsed eddy current, photo-inductive, ultrasound, acoustic emission, and biomedical image/signal processing. (ctai@mail.ncku.edu.tw)