Research on diagnosis of knee osteoarthritis using acoustic emission technique

Tawhidul Islam Khan1,*, Md. Mehedi Hassan2, Moe Kurihara3 and Shuya Ide4

1Faculty of Science and Engineering, Saga University, 1 Honjo-machi, Saga, 840–8502 Japan
2Department of Science and Advanced Technology, Saga University, 1 Honjo-machi, Saga, 840–8502 Japan
3Department of Advanced Health Sciences, Saga University, 1 Honjo-machi, Saga, 840–8502 Japan
4Department of Orthopedic Surgery, Faculty of Medicine, Saga University, 5–1–1 Nabeshima, Saga, 849–8501 Japan

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Abstract: Osteoarthritis (OA) of the knee is a widespread disease caused by the articular cartilage damage, and its prevalence has become a severe public health problem worldwide, especially in the ageing society. Although X-ray, MRI, CT, etc. are commonly used to examine knee OA by inserting external high energy into the body, they do not provide dynamic information on knee joint integrity. In the present research, the acoustic emission (AE) technique has been applied in healthy individuals as well as OA patients in order to evaluate the knee integrity in dynamic analysis modes without inserting any external energy. Four groups of people, young, middle-aged, older, and OA patient have been participated in the present research, and significant results have been identified. It has been found that the degeneration of the articular cartilage progresses gradually with the increase of the age. The angular positions of knee damage are also evaluated by clarifying AE hits. The results are verified through clinical investigations by an orthopedic surgeon applying X-Ray and MRI techniques. The results of the present research demonstrate that the AE technique can be considered as a promising tool for the diagnosis of knee osteoarthritis.

Keywords: Knee joint, Osteoarthritis, Acoustic emission, Integrity analysis, Clinical validation

1. INTRODUCTION

In an ageing society, the numbers of people who complain about pain in their knee joints are mostly due to osteoarthritis (OA). The human knee is a complicated joint, which includes the longest bone of the body and withstand total body weight, including several occasional extra loads, therefore, vulnerable to encounter acute injuries and the development of OA. The knee joint is the prime anatomical structure in the lower extremity and has a great influence on the quality of life and the daily activities in older adults. Daily activities include standing and sitting, walking and running, jumping, stair climbing, deep knee bending such as squatting or sitting Japanese style, and other lower extremity tasks. Knee OA often limits all of these daily activities, particularly in older people, and consequently, they become a burden to society. Therefore, knee OA is a major cause of chronic disability and has become a severe public health problem in the ageing society.

Integrity analysis of knee joint involves a detailed study of anatomical parts (bones, cartilage, muscles, tendons, and ligaments) which interact with the movements of the knee. The anatomy of the knee joint is made up of three bones named the thigh bone (femur), the shin bone (tibia), and the kneecap (patella) and a variety of ligaments [1]. Several muscles and ligaments are responsible for motion control, as well as the protection of the knee joint. There are two crossed in a pair ligaments named anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL), which play an important role in stabilizing the knee and make sure that the weight of the body is transmitted through the center of the joint for minimizing the wear and tear on the cartilage inside the knee [2–4]. Results from
earlier studies show that malalignment causes increased wear, and consequently, permanent failure of the knee joint [5].

OA is the most common type of knee disease, which is caused due to the damage in articular cartilage [6]. It tends to increase gradually from age 40 years old, and it is conspicuous to females than men [7]. OA develops because of the degeneration of tissues constituting the knee joint [8]. Increasing stiffness of ligaments, reducing quality and quantity of synovial fluid, increasing articular surface roughness, reducing cartilage thickness, and reducing muscle strength are the typical changes in knees during the ageing process [9]. Previous research has established that the incidence of knee OA increases with age. Moreover, healthcare professionals believe that the wear of the articular cartilage due to the daily repeated weight-bearing activities of the knee joint increases its risk of OA in ageing. Therefore, knee replacement surgery might be needed if early preventions are not taken [10].

A variety of non-invasive visual imaging techniques, particularly X-ray, magnetic resonance imaging (MRI), and ultrasonic testing (UT), are commonly used to assess knee OA [11]. However, the sensitivity of the present clinical methods exhibits the mixed satisfaction of the patient. All of the mentioned methods need high external energy to insert into the examined parts of the body, which is not always welcomed by the patient. Moreover, almost all of the techniques are utilized in static mode for the diagnosis. Although limited recent use of the MRI has been introduced for the purpose of dynamic analysis, however, the high cost, complexity, and lack of portability features of this system hinder its wide applications as well. In the context of this background, the potential application of acoustic emission technique (AET) is considered for the dynamic analysis of the knee joint [12]. It is considered portable, safe, and user-friendly diagnostic tool for assessing and monitoring knee joint with low cost in dynamic analysis mode.

Acoustic emission (AE) refers to the generation of sonic and ultrasonic sound waves in materials when a material undergoes through the deformation or fracture process. In order to provide a highly sensitive and nondestructive method for monitoring the health of structure, AE technology has been widely applied within civil and mechanical engineering [13]. The technique has been proven invaluable in investigating the dynamic behaviors of materials by enabling both the detection and the location of structural flaws as they develop [14]. Having the advantage of nondestructive damage evaluation, recent interests have been focused on the application of the AE technique to the biomedical applications. Since AE can detect fault formation and propagation in engineering structures, researchers have studied acoustic signals from bone fractures and hip joints as well [15,16]. Crack initiation and propagation in the human femur is also investigated by a single sensor technique [17]. However, due to many artifacts in sensing systems because of extremely inhomogeneity of the knee joint (bone, cartilage, muscle, skin, etc.), continuous efforts in this topic are still due in developing AET as a reliable biomarker. Current research has been done to demonstrate the potential use of the AE technique as a convenient and non-invasive method for damage characterization of the osteoarthritic knee (OA knee) in dynamic modes.

The main objective of the present research is to investigate the condition of knee integrity related to the damages due to the osteoarthritic disease under the dynamic loading to the knee based on AE nondestructive evaluation technique. For this investigation, the acquisitions of AE signals from different ages of people have been emphasized to clarify the ageing effects on degeneration to the knee joint. Three groups of participants, young group (age range 20–39 years old, are considered as complete healthy knee), middle-aged group (age range 40–59 years old, are considered as the initial of cartilage damaged knee), and older group (age range 60 years old and above, are considered as major cartilage damaged knee) are considered. In addition, the damaged knees of OA patients (age range 43–84 years old) are analyzed, and verified their results by the clinical investigations through X-Ray and MRI. We have also received the doctor’s evaluation on the proposed AE diagnosis based on X-Ray, MRI diagnosis of OA patient participants who attended knee operations just after completing the AE diagnosis. Therefore, we have received the reliable comparisons of our proposed technique by the clinical investigations of X-Ray and MRI including doctor’s suggestions. Thus, the present paper represents the complete evaluation system of the proposed AE technique in diagnosis of OA including its initial damage conditions.

Section 2 introduces the hypothesis of the AE diagnosis in the knee joint. Section 3 discusses the AE measurement system and procedure. Section 4 presents the experimental results and discussion. Finally, Sect. 5 concludes the present research.

2. HYPOTHESIS OF AE DIAGNOSIS IN KNEE JOINT

AE wave typically generates in the ultrasonic range with high frequency (≥20kHz) that can be identified within structures under surface interactions. It is identified that the sound is produced from joints during movements due to the friction effects of the cartilage surface in human knee joint [16]. The weight-bearing surfaces (femorotibial joint surface) are degenerated in OA knees due to the microscopic topography of weight-bearing surfaces is
modified [18]. Therefore, severe wear patterns can be produced in cartilage by friction due to the acceleration of daily movements [19]. When extensive frictions happen inside the damage bearing surfaces at the joint, elastic waves are generated, which produce AE events in a broad range of frequency. According to the hypothesis, in a healthy knee, the cartilage surface is smooth and well lubricated; therefore, movement occurs softly and sometimes generates AE signals with low intensity. Whereas, in a damaged knee, the cartilage surface is rough and poorly lubricated; thus, the movement of the damaged knee produces AE signals with high intensity [20].

Figure 1 demonstrates the generation of AE due to the frictional force \( F \), which depends on the condition of the knee cartilage surface. The more the damage in the cartilage surface, the higher the friction coefficient \( \mu' \). When extension (from sitting to fully erect standing position) and flexion (return to seated position) movements occur in the OA knee having higher frictional coefficient, more elastic waves release from the degenerated contact surface of the knee cartilage in terms of AE signals.

3. MEASUREMENT SYSTEM OF ACOUSTIC EMISSION IN KNEE

3.1. Measurement Protocol

The measurement protocol of knee AE has been designed according to the schematic views, as shown in Fig. 2. The measurement system consists of four circular general-purpose piezoelectric sensors (model R6/1 with a frequency range of 35–100 kHz as well as a size of 18 mm in diameter and 17 mm in the thickness of Physical Acoustics Corporation) to attach at the anatomical sites of each knee, four pre-amplifiers (2/4/6 of Physical Acoustics Corporation) to provide 40 dB gain for each sensor, a main AE amplifier (four-channel, Japan Physical Acoustics), an AE acquisition device (four-channel digital oscilloscope, model Tektronix TDS 2024C) and a computer for AE feature storage and post signal processing. The measurement protocol also has an electronic angle measurement system during repeated sit-stand-sit motions, which is from Biometrics and consists of an electrogoniometer (model SG-150) and an amplification unit (model K800). The latter is also linked to the AE signal acquisition device and is driven by the same start trigger sent from the oscilloscope to enable synchronized data acquisition.

The anatomical sites for the attachment of four AE sensors (1–4) are shown in Fig. 3. Among four sensors, two sensors are attached upon the tibia bone, and the other two sensors are attached upon the femur bone. Sensor 1 is attached on the medial condyle of the tibia, sensor 2 is on the medial epicondyle of the femur, sensor 3 is on the lateral condyle of the tibia, and sensor 4 is on the lateral epicondyle of the femur respectively. In order to provide good measurement sensitivity, these specific anatomical sites have been considered (these sensor positions have been investigated as the most sensitive positions for...
receiving AE events and results have already been published [12]) because it offers relative stable sensor positions and less affected by muscle interactions. Although the human knee joint is an inhomogeneous structure, the inhomogeneity effects have been greatly minimized by placing all sensors at these positions, where artifacts due to muscle, skin, etc. are very small and considered negligible. A hypoallergenic medical adhesive tape (ELASTPORE-HADA, NICHIBAN CO., LTD.) with a size of 140 mm × 38 mm has been used to attach AE sensors. Furthermore, to assure continuous contact between the surface of the sensor and the contact place site of the knee, a high vacuum silicone coupling gel (Shin-Etsu HIVAC-G, Shin-Etsu Chemical Co., Ltd.) is applied. Electro-goniometer is positioned laterally using double-sided medical tape so that it can be attached appropriately during the experiment.

3.2. Measurement Procedure
For generating AE signals from the knee joint, it is necessary to provide loads and stresses between frictional surfaces at the joint. Therefore, repeated sit-stand-sit movements have been performed in order for creating joint stress, and thus, facilitating acoustic emissions as a result. Sit-stand-sit actions permit a good degree of control and repeatability and are routinely used in daily life, e.g., knee bending, climbing the stairs, walking, cycling, etc. Each sit-stand-sit action constitutes extension and flexion movements from a standard height chair, with arms folded across the chest. The reason for arms folded across the chest is to remove the influence of the unnecessary movements. Each sit-stand-sit action is considered as one cycle, and three cycles are considered as one set. Sit-stand-sit movements have been counted upon receiving each AE data (AE hit). One-minute intermittent rest time has been taken from one set to another set. Maximum 30 sets have been performed for collecting AE data. The position of the goniometer has been initialized to 90° at the sitting position, while at the standing position, it has been set to 0°. Thus, in one cycle of movement (sit-stand-sit), the measured angle has been recorded as 180°. For the acquisition of AE signals, 1 MHz sampling frequency is used, while 100 Hz sampling frequency is utilized for the acquisition of angular output signals from the electro-goniometer. One AE hit (AE hit is defined as the detection of an AE signal on a channel) in waveform is represented in Fig. 4, where the maximum amplitude is shown along with other parameters.

4. EXPERIMENTAL RESULTS AND DISCUSSION
The present experiment has been conducted focusing on the primary objectives of the research in the identification of knee problems by applying the AE technique. This work is the continuation of our previous work, where only two groups of people (young and aged) were considered for the clarification of the sensitivity in AE data acquisition system [12]. However, the present paper represents the complete evaluation system of the proposed AE technique in diagnosis of knee OA damage. The research has been focused on two major parts. One part consists of different aged people of total 41 participants without any knee problem. The participants are considered as healthy people (self-declared) since they never went to the hospital for their knee problems. Another part consists of knee patients who have been taking treatment, including knee surgery for their knee problems of OA disease (detailed discussions about results are given later). Again, participants without any knee problems have been categorized into three groups based on their ages. Among the three groups, group A is categorized as for young people (20–39 years old, where the average age is 22.7), group B is categorized as for middle-aged people (40–59 years old, where the average age is 49.3), and group C is categorized as for older people (60 years old and above, where the average age is 65.9). Among 41 participants, 12 participants belong to the group A, 12 participants belong to the group B, and the remaining 17 participants belong to the group C. The objective of this part is to determine the effects of ageing in degeneration on anatomical components of the knee joint. Accordingly, experimental results of the knee joint integrity analysis among participants of different ages have been summarized as follows.

4.1. AE Incidence Analysis for Different Age Groups
In order to compare the knee conditions among participants of three aged groups, AE incidence analysis has been conducted. AE incidence for each participant is
clarified based on the total number of required sit-stand-sit actions for a fixed number of acquired AE hits. The number of AE hits has been fixed to 10 hits as the minimum number in the present analysis based on the young participant’s hit number. As young participants possess healthy knees, they are required many sit-stand-sit motions for getting 10 AE hits. On the other hand, older participants need fewer sit-stand-sit motions for getting 10 hits as they possess aged knees. Thus, 10 AE hits have been considered in percent incidence (PI) calculation for the all groups of participants in the evaluation of their results. PI is calculated by the following equation.

\[
PI = \frac{n_{AE}}{n_{STS}} \times 100
\]  

(1)

where, \(n_{AE}\) indicates the fixed number of AE hits, and \(n_{STS}\) indicates the total required sit-stand-sit motions.

The PI for each person of each group has been calculated based on the above equation, and the group averaging has been done by averaging the values of all participants in each group, and finally, the PI for all groups have been compared. Numerical results of PI analysis are summarized in Table 1. Results in this table compare the PI analysis of AE hits obtained from three different age groups. It is identified that the PI value increases with the increase of the age, and thus, the group C (older group) has reported the highest increase in PI compared to other groups of participants. The result is significantly found in comparison with group A (young group) participants as well. Therefore, it is considered that the AE incidence (PI) increases due to the decrease of the surface condition of the knee cartilage [21]. What stands out in this analysis that the degeneration process progresses gradually as the age of the people increases.

Thus, according to the observation, the percent incidence of AE hits can work as an acceptable biomarker for knee integrity analysis.

Furthermore, standard deviation (SD) of PI for groups A, B, and C have been calculated and shown in Table 1 as well. From the result of SD, it is seen that PI varies based on participants’ knee condition. Although, group A represents young group, however, their SD increases than group C. The reason is that two participants in this group have shown higher PI due to their abnormal knee conditions. The same effects are observed in group B as well. These situations are considered to mitigate by increasing the number of participants in future experiments.

### 4.2. AE Amplitude Analysis for Different Age Groups

The comparative investigation of AE amplitude for understanding the degenerative process of articular cartilage of knee joint has performed, and remarkable changes are identified among young, middle-aged, and older people groups. AE amplitudes for all groups have been compared by averaging the amplitudes of all participants in each group. Average numerical values of AE amplitude analysis (in volts as well as in dB) along with their standard deviation (SD) are summarized in Table 2, where comparison of the average maximum amplitude analysis is shown. Similar results are also confirmed by comparing the percent incidence of AE hits in the previous section. As the magnitudes of AE signal amplitudes depend on the intensity of generated elastic wave, in the present experiment, AE signal amplitudes are obtained similarly due to the frictional effects of the knee cartilage during the sit-stand-sit movements of the participants. Therefore, the surface condition of the knee cartilage is a major considered criterion in increasing the signal amplitudes. For the young group of people (group A), the conditions of their knees are expected to be healthy, and therefore, the amplitudes of acquired AE signals are obtained small. On the other hand, amplitudes of acquired AE signals are obtained higher in the case of older group of people (group C). It is thought that the articular cartilage of their knees have received erosions as they have undergone the ageing process, and thus, generated higher amplitude of AE signals. Likewise, participants of group B also exhibit increasing signal amplitude compared with group A participants, however, it is much less than group C. As the increasing difference between group A (healthy knee) and group B is very small (around 1 dB), hence, it can be considered that the surface condition of knee cartilage has been started degrading as well in group B [21,22]. The observations are found in the standard deviation analysis in the next paragraph as well.

The standard deviations (SD) of maximum amplitude distribution are calculated for group A, group B, and

| Table 1 | Average percent incidence of three age groups along with their standard deviation. |
|---------|---------------------------------|
| **Age group** | **A** | **B** | **C** |
| Age range | 20–39 | 40–59 | 60 and above |
| Average PI [%] | 39.7 | 53.5 | 69.5 |
| Standard deviation | 35.2 | 36.1 | 32.3 |

| Table 2 | Average maximum amplitude of three age groups along with their standard deviation. |
|---------|---------------------------------|
| **Age group** | **A** | **B** | **C** |
| Age range | 20–39 | 40–59 | 60 and above |
| Average maximum amplitude, V (dB) | (114.1) | (115.1) | (119.7) |
| Standard deviation | 0.35 | 0.64 | 1.58 |
group C as well. It is seen that group C shows the highest SD compared to that of group A and group B. The SD of group B is almost twice, and the SD of group C is almost five times compared to the SD of group A. As the difference of SD between group A and group B is smaller than the difference of SD between group A and group C, this difference in SD indicates that the knee starts to damage in group B and become worse when people grew older. Furthermore, the larger SD indicates the larger spread out of amplitude distribution concentration. Therefore, the observation clarifies that the cartilage damage of the knee joint in older participants is higher compared to the young and middle-aged participants.

Statistical analysis for amplitude distribution of acquired AE signals is conducted in order to focus on the significant amplitude differences among the three groups of participants. The results are shown in Fig. 5. In this figure, $R_A$, $R_B$, $R_C$ indicate the ranges in which most of the maximum amplitudes of AE signals are concentrated for the group of young, middle-aged, and older participants, respectively. From the figure, it can be seen that most of the amplitude values of group A (96% of total values) are concentrated within 1.80 V in $R_A$. Similarly, the amplitude values of group B are concentrated within 2.32 V in $R_B$. In the case of group C, the amplitude values are concentrated within 4.60 V in $R_C$. It is evident that the range of the amplitude values increases with the increase of the age ($R_A < R_B < R_C$). Therefore, the concentration distribution of AE amplitudes gradually progresses with the progression of the degeneration of the knee joint, and it is greatly influenced by the ageing process.

Thus, based on the above analysis, the maximum amplitude of AE hit can be considered as a reliable indicator for the integrity analysis of the knee joint as well.

4.3. Power Spectrum Analysis of AE Signals

A comparative study of power spectrum analysis has been carried out among young, middle-aged, and older people denoted by group A, B, C respectively, and significant differences are found. In this analysis, the maximum power spectrum ($V^2/Hz$) is calculated for all participants of three age groups (A, B, C). In order to transform the AE signal into frequency domain, Fast Fourier Transform (FFT) calculations have been conducted by using the Eq. (2).

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi kn/N}$$  \hspace{1cm} (2)

$$P_{xx}(k) = \frac{|X(k)|^2}{L}$$  \hspace{1cm} (3)

Here, $x(n)$ represents the discrete time AE signal of each person for all group of participants in domain. The signal has been sampled with $N$ sized window, and $L$ frequency point has been considered for FFT calculations. The power spectrum of each signal of all participants of three age groups has been calculated by using Eq. (3). The average of maximum values of power spectrum has been evaluated for the three age groups and plotted in Fig. 6 for comparing among the groups. The comparison of the average of maximum value of AE signal in frequency domain shows that this value increases significantly with the increase of ages. Therefore, this comparison suggestively gives an indication that the damage in the knee produces higher magnitude of AE data for ageing people than the younger one.

4.4. Analysis of OA Knees from Patient Participants

The ageing effects to OA knee have been analyzed by the AE technique in the previous section. In the present section, the AE technique has been verified as a clinical diagnostic tool for the identification of knee damage due to the OA. Related experiments have been conducted with...
OA patients at Saga University Hospital. AE diagnostic experiments have been conducted just before the patient’s knee surgery. Thus, the obtained AE data from all patients have been verified with their X-Ray and MRI data along with the related doctor’s evaluation. All participants joined the experiments following the ethical declarations and procedures of the Saga University by submitting their written consents before joining the experiments. Results are discussed in the following sub-subsections.

4.4.1. Comparison of AE incidence between healthy knee and OA knee

The incidence analysis of AE signals received from the knee joints of the patient group has been conducted and compared with the healthy groups for understanding the damage condition of OA knees comparing with the healthy knees. A total of 23 OA patients have been participated in the present experiments. Percent incidence (PI) for the patient group is also calculated according to the calculations as explained in Sect. 4.1. The results of PI analysis of OA patients have been compared with healthy groups (A, B, C) and the comparisons are shown in Fig. 7. In this figure, the AE incidence of all patient participants is represented in a group of D. Although the young group of participants (group A) produce AE hits, which are generated due to the general frictional behavior of the smoother surface interaction inside their knee joints, the AE hits are relatively smaller than the AE hits received from the patients, which satisfy the hypothesis as well. It is found that PI value increases with the increase of age. Furthermore, due to larger knee damage, group D (patient group) has reported the highest increase in PI comparing with other groups of participants. A significant difference (almost double) in percent incidence between the young and the patient groups has been observed. It is considered that this AE incidence difference has been occurred due to the occurrence of increased AE incidence from the damaged frictional surface inside the patient’s knee joint. This significant difference, thus, indicates that the AE incidence evaluation can be a reliable biomarker in identifying the healthy knee and the damaged knee.

4.4.2. Differentiate patients of $D_a$ and $D_m$ by the spectrum analysis of AE signals

In this section, the damage characteristics of the knee joint between articular cartilage damaged patients ($D_a$) and meniscus damaged patients ($D_m$) have been clarified by the spectrum analysis. Among 23 OA patients, 13 participants were articular cartilage damaged patients, mentioned as $D_a$, and 10 participants were meniscus damaged patients, mentioned as $D_m$. The age range of group $D_a$ is 57–84 years, where the average age is 68.1 years. Similarly, the age range of group $D_m$ is 43–64 years, where the average age is 56.1 years. Accordingly, power spectrum analysis and peak frequency distribution analysis are conducted between two groups of patients. Power spectrum analysis for all patient participants of $D_a$ and $D_m$ by applying the FFT algorithm shows the considerable differences between the two groups, as represented in Fig. 8. The average energy content of obtained AE signals represented in power spectrum is compared between two groups of patients in this figure. Results show that the mean power spectrum value for articular cartilage damaged patients is higher compared to that of meniscus damaged patients. These differences are further clarified by the analysis of the peak frequency distributions of two groups of patients and the results are shown in Fig. 9. It is already mentioned that AE sensors with a frequency range of 35–100 kHz (model R60/C11) are used for the present experiment. Therefore, results are presented in the figure according to the frequency range of the sensor. From the figure (Fig. 9), it is seen that the distribution of the peak frequency is less spread out for group $D_m$, whereas, group $D_a$ distribution pattern is more spread out in comparison with group $D_m$. The results
signify that the magnitude of the meniscus damage is smaller than the articular cartilage damage. The similar difference has also been observed from the analysis of the power spectrum (Fig. 8). Thus, from both analysis, it is found that AE hits received from the articular cartilage damaged patients are higher compared to that of the meniscus-damaged patients. It is thought that the result has been happened due to the larger damaged area of the articular cartilage compared to that of the meniscus during the dynamic movements of the knee joint. Therefore, the obtained spectrum values and peak frequency distributions of AE signals are larger in group \( D_a \) compared to group \( D_m \).

4.4.3. Angular distribution of AE hits and clinical verification for damage location of OA knees

In this analysis, the knee angles have been measured by using an electronic goniometer (as explained in Sect. 3.2) in order to find the damage locations of OA knee. AE hits that are received from the knee joint movements by sit-stand-sit actions are represented in the angular distribution diagrams of knee joints. One sample result of one patient participant from group \( D_a \) are summarized in Table 3, where the percent of AE hit concentrations according to the range of knee angles are presented numerically. The distribution of total acquired AE hits for two cycles of sit-stand-sit movements of the same patient is shown graphically in Fig. 10 as well. Accordingly, it has been considered that AE hits (solid circles in the figure) have been concentrated to the damaged position of the knee joint. It is already mentioned that each cycle started at 90 degrees angle of knee movement (seated position). The hit distribution of AE signals from the OA patient shows that most of the AE data (75%) have been concentrated to a particular angular distribution range, and that range is shown in the figure (Fig. 10) as 30–60 degrees. It is also found that 25% of AE hits are distributed within 60–90 degrees of knee angles. However, in the next three movements, all AE data have been distributed to the range of 30–60 degrees, and there is no data distribution in 60–90 degrees, which have been found only in the beginning stage of the movement. Therefore, it is thought that this is a deviation in AE hit concentrations, which has been happened due to the static effects of the knee movements at its beginning stage. The result is verified with the X-Ray investigation of the same patient diagnosed by an orthopedic surgeon, and the result is shown in Fig. 11. The X-Ray investigation also shows that the damage in the knee joint of the patient is located at 30–60 degrees of knee angels. In that area of 30–60 degrees, osteosclerotic change and joint surface irregularity of the femur surface and the opposite tibial surface are observed as well. Similarly, the remaining patients of group \( D_a \) have also been analyzed by the angular distribution diagram as well as X-Ray investigation with doctor’s evaluation. It is found that AE hit distributions for the all-patient participants have been concentrated to the damaged angular positions according to their knee conditions.

In the similar way, the numerical and the graphical representations of AE hit concentration for one patient from the group \( D_m \) are explained in Table 4 and Fig. 12, respectively. The distribution of AE hits of the patient indicates that the most of the AE data (72.2% in Table 4) have been concentrated within the range of 0–30 degrees’ angular position, which is shown in Fig. 12.
found that 11.1% of AE hits are distributed within 60–90 degrees, and 16.7% of AE hits are distributed within 30–60 degrees of knee angles. It is thought that the scattered distributions of AE hits at 60–90 degrees and 30–60 degrees have been occurred due to the less surface damage of the knee joint, whereas the major AE hit distributions have occurred at the severely damaged area of 0–30 degrees. These findings are further verified with the X-Ray and MRI investigations diagnosed by the orthopedic surgeon and shown in Figs. 13 and 14 respectively. Osteosclerotic change and joint surface irregularity of the femur surface and the opposite tibial surface are observed in the area of 0–30 degrees on the X-Ray. Similarly on the MRI, an irregularity of the cartilage surface and a subchondral bone sclerotic change have been observed in both the femur and tibia, and the anterior lesion of the medial meniscus is admitted as well. Therefore, X-Ray and MRI analysis also reveal that the major knee joint injury for the patient has occurred at 0–30 degrees of knee

Table 4  AE hit concentration to angular distribution, group D_m.

| Angle range (°) | AE hit concentration [%] |
|-----------------|--------------------------|
| 90–60           | 11.1                     |
| 60–30           | 16.7                     |
| 30–0            | 72.2                     |

Fig. 12  Angular distribution of AE hits from a patient of group D_m.

Fig. 13  X-Ray result from a patient of group D_m.

Fig. 14  Meniscus damage evaluation by MRI analysis from a patient of group D_m.
angels. Similarly, the angular distribution diagram as well as X-Ray and MRI analysis with doctor’s evaluation have been analyzed for the remaining patients of group Dm. It is found that according to their knee conditions, AE hit distributions for the all patient participants have been concentrated to their damaged angular positions. It is mentioned that the MRI investigation has been additionally performed by the doctor’s suggestion for the proper investigation of the meniscus damage for the patient participants of group Dm.

Therefore, based on the above observations, it can be concluded that the concentrated distribution of AE hits can reveal the damaged area in knee integrity analysis.

5. CONCLUSIONS

In this research, the acoustic emission technique has been applied to evaluate the integrity of the knee joint related to the damages due to osteoarthritic disease. This analysis has examined the role of ageing in the degeneration of the knee joint. The damage diagnosis of OA patients has been conducted by the AE technique as well, along with the clinical investigations, including the related doctor’s evaluations. Four groups of people, young, middle-aged, older, and OA patient, have been participated in the analysis, and the major findings are concluded as follows:

One important finding emerges from this research that the degeneration of the articular cartilage has been influenced due to ageing, and the degeneration process progresses gradually as the age of the people increases.

The damage characteristics of knee joints have been identified successfully for OA patients. The frictional surface of the damaged knee of OA patient increases the AE incidence compared with the healthy knee, is also clarified in this analysis. The damage conditions of knee joints between patients of articular cartilage damage (Dm) and meniscus damage (Dm) have been characterized by the spectrum analysis of AE signals as well.

The damaged area of the knee joint has also been identified by clarifying AE hits with respect to the angular position evaluation. X-Ray and MRI examinations are also employed successfully in the present research for the validations of the results from AE diagnosis.

All these findings clearly indicate that the acoustic emission technique can be worked as an acceptable promising tool for the diagnosis of the knee osteoarthritis.

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The authors declare that they have no conflict of interest.

ETHICS APPROVAL

The research has been approved by the ethics committee of Saga University, Japan.
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Tawhidul Islam Khan graduated from the Department of Mechanical Engineering, KUET, Bangladesh in 1991. He completed his masters and doctorate degrees from Saga University, Japan in 1997 and 2003 respectively. After his Ph.D., he awarded the JSPS postdoctoral fellowship and continued his research at Saga University until September, 2007. He is working as an Associate Professor in the Department of Mechanical Engineering of Saga University, Japan. His current research interests are intelligent machines, acoustic emission in NDE, diagnostics, biomedical imaging, noise reduction, signal processing and image processing. He is the author of more than 120 technical papers. He is the member of IIAV, SICE, ASJ, JSME, SOPEJ and IEB.

Md. Mehedi Hassan is currently a Ph.D. student in the field of biomedical engineering in the Department of Science and Advanced Technology of Saga University, Japan. He received his B.Sc. (Eng.) degree in Mechanical Engineering from Chittagong University of Engineering and Technology (CUET), Bangladesh, in 2015. He obtained his M.Eng. degree in the Department of Advanced Technology Fusion from Saga University in 2018. At present, he is doing research in AE source location for advanced applications in biomedical engineering and structural health monitoring.

Moe Kurihara grew up in Saga, Japan. She spent four years in Mechanical Systems Engineering at Saga University and graduated in 2020. She is currently a master course student at Saga University. She is doing research on diagnostics using acoustic emission (AE) signal processing in knee joints.

Shuya Ide received his doctor’s license from Saga University. He is currently a hospital director of orthopedics clinic. His main interests include biomechanics and surgery of the knee joint.

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