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REVIEW ARTICLE

Hip implant performance prediction by acoustic emission techniques: a review

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Abstract

Nowadays, acoustic emission (AE) has its applications in various areas, including mechanical, civil, underwater acoustics, and biomedical engineering. It is a non-destructive evaluation (NDE) and a non-intrusive method to detect active damage mechanisms such as crack growth, delamination, and processes such as friction, continuous wear, etc. The application of AE in orthopedics, especially in hip implant monitoring, is an emerging research field. This article presents a thorough literature review associated with the implementation of acoustic emission as a diagnostic tool for total hip replacement (THR) implants. Structural health monitoring of an implant via acoustic emission and vibration analysis is an evolving research area in the field of biomedical engineering. A review of the literature reveals a lack of reliable, non-invasive, and non-traumatic early warning methods to evaluate implant loosening that can help to identify patients at risk for osteolysis prior to implant failure. Developing an intelligent acoustic emission technique with excellent condition monitoring capabilities will be an achievement of great importance that fills the gaps or drawbacks associated with osteolysis/implant failure.

Keywords Total hip replacement (THR) · Acoustic emission (AE) · Microcracks · Microdamage · Implant failure

1 Introduction

Total hip replacement (THR) surgery is a major surgical procedure where damaged portions of the hip joint are replaced with prosthetic components that are made of metal, ceramic, and plastic [1]. That is, the femoral head is replaced with a prosthetic head with a stem to support it, and the acetabulum is replaced with a prosthetic cup. Metal-on-polyethylene, ceramic-on-polyethylene, metal-on-metal, ceramic-on-ceramic, and ceramic-on-metal components are existing THR implants available in the USA. Each hip prosthesis is unique depending on its size, material, and the dimensions employed for its design.

Current global statistics show that yearly, more than 1.2 million patients receive THR as a treatment for hip disorders associated with trauma and degenerative conditions like osteoarthritis [1–3]. By the year 2030, it is estimated that the number of THRs performed in the USA will increase by 174% (572K), primarily due to the increasing number of older patients in the target demographic [1]. People affected with symptoms of osteoarthritis will be advised to replace the affected joint with an artificial hip implant as it progresses to the loss of joint function. The THR surgery (primary THR) with an average lifespan of around 15 years [1] is a significant surgical achievement that has helped many patients to overcome the hip joint pain and restore day-to-day functions with little restrictions in lifestyle. Even with recent drastic enhancements in primary THR surgery, chances of secondary replacement surgery are high due to aseptic loosening caused by particle-induced osteolysis.

Anatomy of a typical hip joint and a defective hip joint with osteoarthritis is depicted in Fig. 1. Since the 1960s, THR in which the damaged bone and cartilage are removed and replaced with prosthetic components is considered as the best

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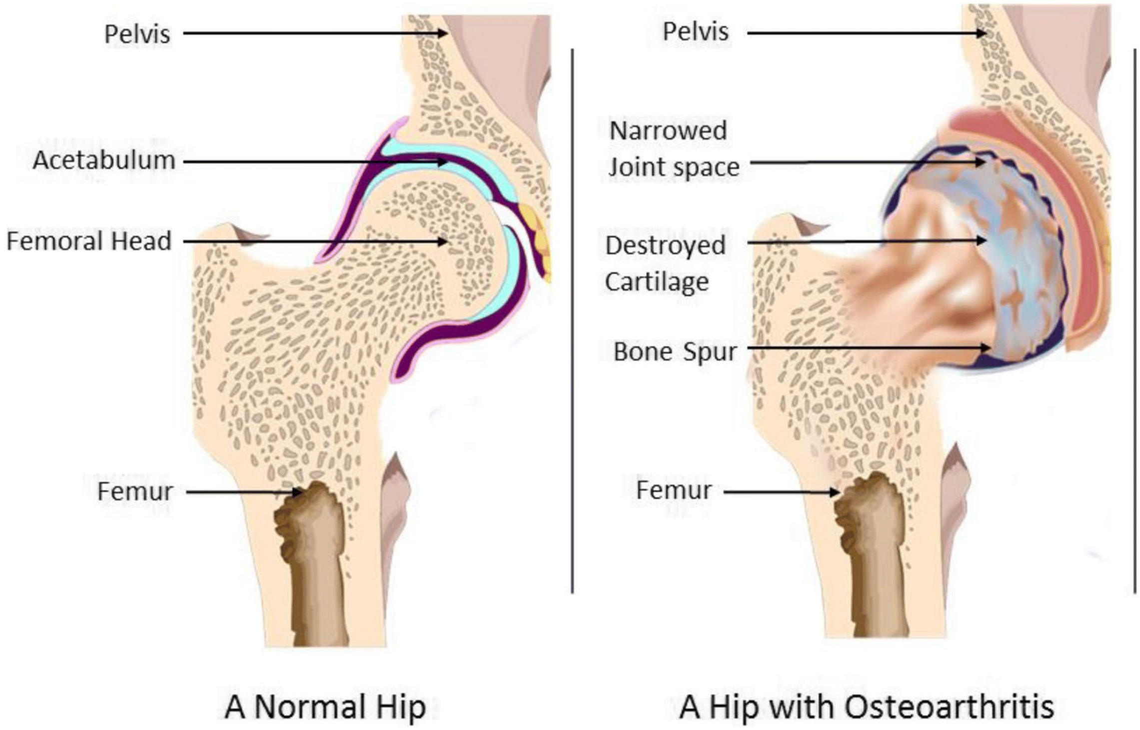

Fig. 1 The effect of arthritis on the normal function of a hip joint

solution for osteoarthritis, rheumatoid arthritis, post-traumatic arthritis, avascular necrosis, and childhood hip disease. A schematic diagram of a THR implant is shown in Fig. 2.

The importance of revision surgery arises when aseptic loosening occurs within the primary THR. Other causes of implant failure include infections, breaking of bone as well as prosthesis, and other complications [4, 5]. Even though secondary revision surgery is advisable, it is slightly more complicated considering the quality of the bone, satisfactory adaptability of the revision hip in position, and patient's age. By the time revision surgery is suggested, the patient may be older and perhaps less tolerant of the lengthy surgical procedure. By considering all the factors, revision surgery must be carefully considered and planned [6, 7].

Failures associated with THR implants reside mainly in head-cup, modular junction, and stem-bone interfaces. Currently, revision surgery is the only treatment for osteolysis, but with higher failure rates [8], higher patient mortality rates [9], and worse pain and functional outcomes than primary THR even with substantial bone loss prior to revision surgery [10]. From this, it is evident that periodic monitoring of THR implants is inevitable. Many techniques have been proposed for monitoring hip joints like post mortem examination, arthrography, digital radiography, dual-energy X-ray absorptiometry (DEXA), and Roentgen stereo-photogrammetric analysis (RSA), vibration technique, acoustic emission (AE) method, and so on.

AE offers a non-invasive and non-destructive method to observe the structural degradations of a THR continuously.

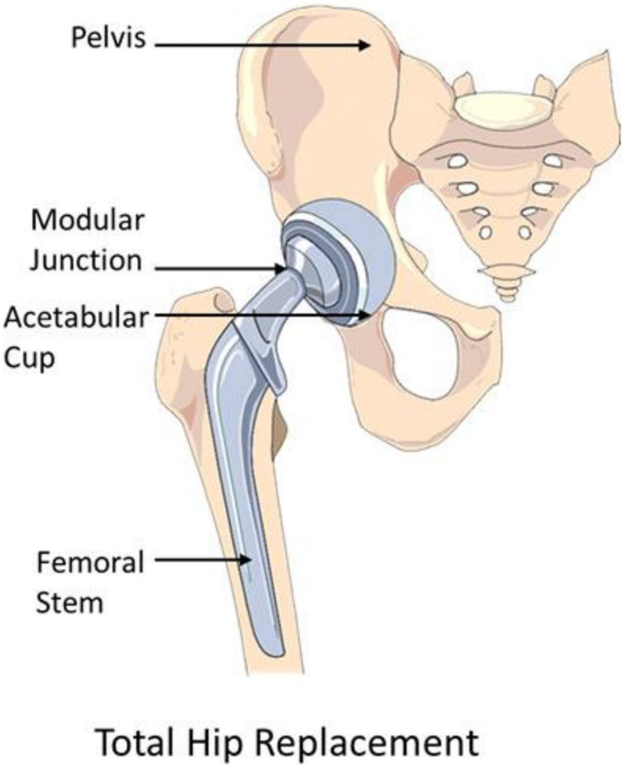

Fig. 2 The total hip replacement (THR) with three components, femoral stem, head, and cup. The junction between stem and head is called modular junction. This is end-stage clinical intervention of the patients who suffers hip-related arthritis

This technique detects both internal and global flaws, a quality that other methods such as ultrasonic and radiographic techniques cannot obtain. For example, the presence of material degradation such as crack initiation or propagation will emit a specific, abnormal AE signal. Through its passive structural evaluations, detecting this signal can provide valuable information on the progression of the implant flaws and early-stage complications. THR complications can be addressed before the development of irreversible damage by identifying and analyzing early-stage elastic stress waves induced by material degradations, which can prevent the development of irreversible damage. Unfortunately, currently utilized methods can only detect implant failure, leading to the inevitable need for revision surgery. Revision surgeries put the patient at a higher risk of developing further complications such as infection or overall implant failure, so it is important to detect complications early on. Therefore, AE is an inexpensive and cost-efficient method to identify complications and provide valuable insight to healthcare providers.

This paper addresses the importance and competence of AE in the early identification of flaws associated with THR implants. The basics of AE and a comprehensive review of recent studies on the use of the AE for hip implant monitoring are presented. Finally, the current challenges and new direction of research are included.

2 Acoustic emission: basic principles

AE process is a passive method that "listens in" on a mechanical loading event (Fig. 3) [11]. When forces act on a body, they produce stress that causes deformation and energy releases. This released energy travels in the form of stress waves with high frequency that may cause structural deformation and breakdown of the material at specific places. When this material breakdown takes place, it generates elastic/stress waves or oscillations later converted to an electric signal that is then captured by a remote sensor. Analysis of these AE data involves characterization of these received signals to its source location, voltage intensity, and frequency content. Sources of AE can be fractures, cracks, wear, plastic deformation, phase transformation, chemical reaction, Magneto-Acoustic emission, and pseudo-acoustic emission sources [12] .

2.1 Acoustic emission signal analysis

AE is crucial in determining the dynamic behavior of materials in hip replacement implants. AE signals generated as part of the stress or loading activities will be recorded with information such as the source and medium of propagation as well as AE sensor and electrical instruments used.

The transfer function of AE (H_{AE}) signal in the frequency domain is expressed as the product of transfer functions of the source H_s, propagation medium H_m, sensor H_t and electronics H_e [13–15] Elastic waves are propagated associated to any transient changes in the local stress and strain fields within a material.

$$H_{AE} = H_s * H_m * H_t * H_e \tag{1}$$

This study on the transfer functions of the components of the measuring chain, such as material, sensor, transducer, and electronic systems, demonstrates that it is difficult to separate micro-

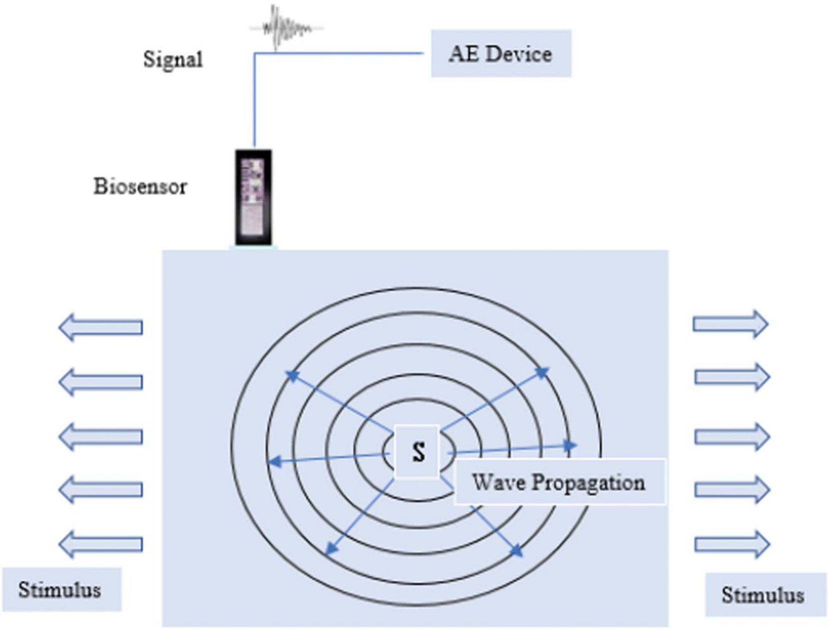

Fig. 3 Schematic diagram for acoustic emission generation

failure mechanisms in material composite (in this study, polymer-matrix composites) from the frequency spectra of AE signals. The important source information can be distorted by the high attenuation of polymer materials related to high-frequency parts of stress waves and transducer's transfer function. Hence, in AE signal analysis, it is important to examine the source function, transfer function of wave-guiding medium, the geometry of the examined structure, and transducer characteristics.

AE signals generated as part of the stress or loading activities will be captured, and signal features such as amplitude, rise time, duration, energy, and counts are measured for the implant's integrity measurement. Detected elastic waves are liable to attenuation because of source-to-transducer distance and orientation relationships. These attenuations may arise due to material attenuation/scattering and geometrical spreading of the elastic waves. Reduction in the amplitude of high-frequency components of these waveforms is a measurable effect of material attenuation. Typical parameters that can be taken into consideration when dealing with AE are depicted in (Fig. 4) [10–12, 16–18].

The time interval between the first threshold crossing and the signal peak is termed as rise time, R, which identifies the signal qualification and is used in noise filtering. Duration, D, measured in microseconds corresponds to the time difference between first and last threshold crossings; it helps in identifying different types of sources and noise filtering.

1. Amplitude analysis

Amplitude, A, represents the greatest measured voltage in decibels (dB) that helps in determining signal detection above a defined threshold. These voltage signal amplitudes are plotted as distributions that help to determine the level of disturbance of the specimen, such as crack growth and crack propagation.

2. Frequency analysis

AE waveform after amplification is recorded and digitized to perform frequency analysis using signal transforms. This frequency analysis gives information about rising time and different deformation/fracture types. Average frequency is evaluated in kHz.

3. Energy analysis

Energy counts or MARSE (measured area under the rectified signal envelope), E, is an important measure of signal size that corresponds to the area within the dotted lines (as shown in Fig. 4) of the voltage-time envelope. AE energy is assumed to be proportional to the integral of the square of transducer output voltage [15]. Energy is calculated after amplification of 80–100 dB over a 1 MHz limited bandwidth.

4. Counting

Counts, *N*, denote the number of pulses that can be one or many, in the captured signal wherein signal amplitude is greater than the threshold value. *N* can be used to measure the quality information about the shape of a signal when combined with other parameters such as amplitude and duration.

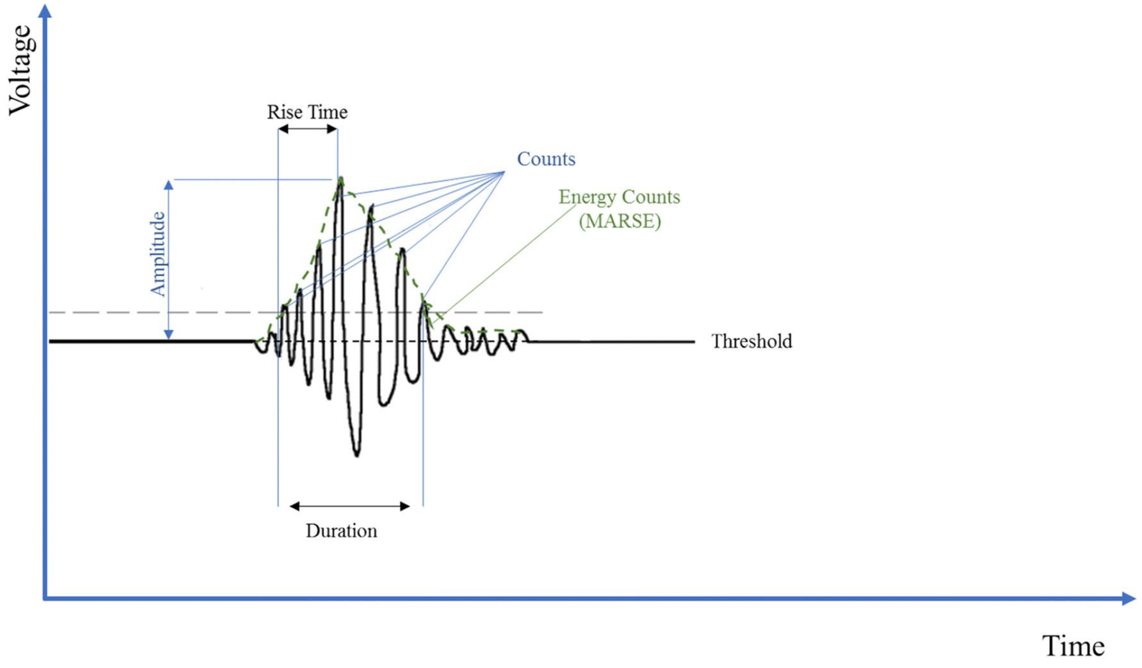

Fig. 4 Acoustic emission parameters and basic concepts

2.2 Acoustic emission sensors

AE sensors are built on listening to high-frequency elastic waves and interpret the stress waves from the material deformations into usable AE waveforms [19, 20]. Transducer elements in each AE sensor respond to dynamic motions associated with AE events that convert elastic waves into electrical signals dependent on its sensitivity, directivity, and frequency response characteristics [21]. Thus, AE sensors enable continuous monitoring of structures to locate the presence of damage. Based on these characteristics, AE sensors can be categorized as resonant or broadband AE sensors. It is understood that an ideal AE sensor is capable of measuring over the full frequency bandwidth of the signals [20]. Resonant sensors are made of piezoelectric materials such as PZT ceramic and are very sensitive at its resonant frequency. On the other hand, broadband sensors, which are not sensitive enough at its resonant frequency, are of a capacitive type or laser interferometers. Resonant sensors are the most commonly used in AE measurements.

In mechanical engineering systems, preventive maintenance involves the routine monitoring of mechanical parts and components in critical roles. This article proposes migrating that concept from machinery to the hip implants. Implementing such a protocol in the early diagnosis of failure in THR is of great importance in the context of monitoring "in-service" life of around 12–15 years and thereby identify implants prior to failure. That is where AE has a sizable opportunity to be deployed as the evaluation method of choice in orthopedics.

Kapur et al. [22] showed that AE evaluation had been widely used as a research tool in evaluating biomechanical properties of bone and in detecting microdamages. More recently, its usage has been extended in orthopedic pathology, including diagnosis of articular wear in the knee and early hip prosthesis loosening, monitor fracture healing, and callus yield strength as well as diagnosis of soft tissue and spinal injury. According to this survey, the future use of AE technology in orthopedics is undoubtedly an exciting and fast-expanding area of contemporary research with extensive clinical potential.

3 Acoustic emission as a hip implant monitoring—previous studies

With THR surgery, the damaged portion(s) of the hip joint are replaced with artificial implants to resume mobility and relieve pain that occurred due to arthritis or other hip-related problems. Factors such as patient's age, sex, weight, diagnosis, activity level, conditions of the surgery, and type of implant chosen, determine the durability of these implants.

An example of the in vitro hip joint test setup is shown in Fig. 5, even though the experimental set up varies with different procedures as discussed below. In vivo studies using AE technique in THR is depicted in Fig. 6 where embedded biosensors sense the changes occurring in hip implant, and transmitters transmit it to the desired access point such as a smartphone that records the signal details and stored for later studies. This section reviews existing AE studies to assess risk or complications associated with THR Implants [23, 24].

3.1 Aseptic loosening

The structural integrity of THR implants for various physical/stressing/loading activities can be analyzed by monitoring AE signals. Davies et al. [25] investigated when, where, and to what extent the cement-metal debonding occurred in a simulated single-leg stance that may eventually lead to the loosening of cemented femoral components of THR. In this study, AE monitoring is performed continually, whereas ultrasonic evaluation on a daily basis and revealed that with each major bursts of AE, the ultrasound showed the presence of debonding. Fatigue testing on implants was conducted for various loading cycles by making two groups of three specimens each. Results dictate that an increase in AE correlates to a change in ultrasonic waveform from bonded to debonded at the stem-interface, which confirmed through the microscopic evaluation. These findings demonstrate the AE technique can be used for the THR monitoring. An in vitro non-destructive evaluation has been conducted by Browne et al. [26], which helps to quantify the failure mechanisms related to the loosening of cemented hip joint replacements. In this work, initiation and progression of failure during fatigue tests are monitored by AE sensors. Experiments revealed that AE has the potential to be used as a tool for preclinical assessment of THR, which can provide a detailed understanding of the internal crack propagation and delamination patterns. Applicability of frequency resonance measurement (FRM) in the detection of loosening metal hip endoprosthesis is studied in detail by Paech et al. [27]. In another work [28], the same investigators used frequency resonance monitoring (FRM), for diagnosing loosening in hip arthroplasty where the specimens used are different cow bone models with varying types of hip implants in soft tissue simulators. The AE signals are high-frequency waves compared to regular frequency monitoring. Gao et al. [29] developed a new evaluation method for the early loosening detection of the artificial hip joint by AE technique. In this study, patients are advised to do specific movements, and the AE emitted during these movements are recorded and analyzed by an FFT analyzer. Obtained results were compared with

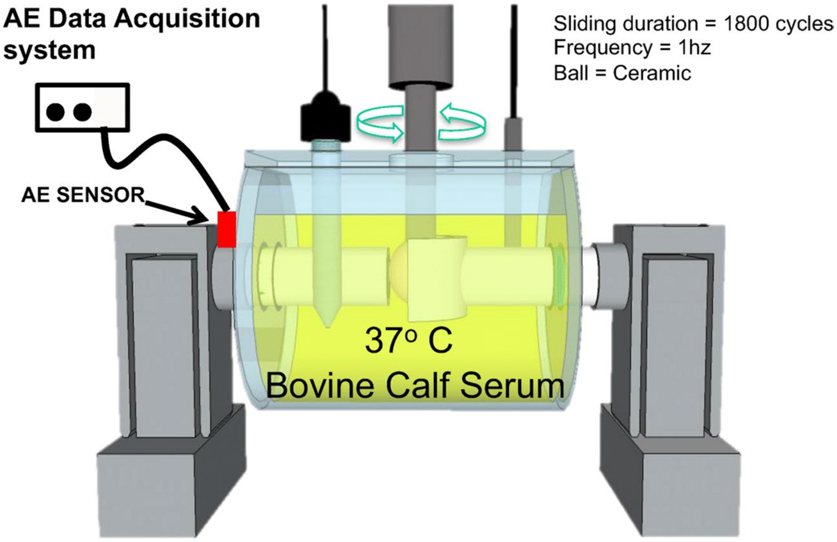

Fig. 5 Experimental setup (in vitro model) to monitor tribocorrosion in conjunction with acoustic emission

the corresponding X-ray and clinical observations. Results reveal that AE frequency components provide dynamic information and showed some abnormal results which were not observed in the X-ray. This method is proved that AE evaluation can detect early loosening of THR which is not possible by X-ray inspection. To understand more clinical applicability of the AE, a human cadaver (dead body) model study [30], the potential application of resonance frequency monitoring (RFM) is evaluated as a non-invasive and non-traumatic method to monitor loosening and interface problems in hip replacement. The main outcome of the study is that acoustic studies are highly sensitive for hip conditions but require further clinical and experimental studies. A new approach [31] in the diagnosis of an endoprosthetic implant loosening is proposed based on the transmission of an internally generated combined acoustic and vibration signal.

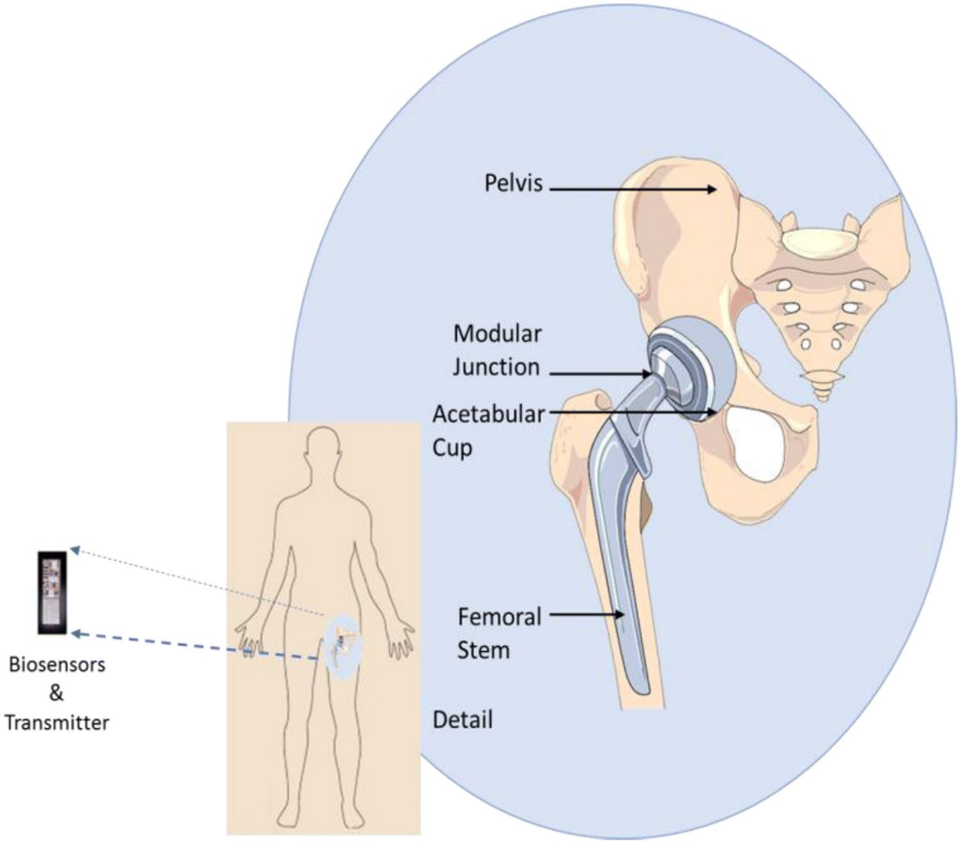

Fig. 6 Potential use of the acoustic emission sensors to monitor THR performance and failure process

3.2 Aging/degradation

Monitoring aging/degradation of the THR is investigated by many investigators. In 2003, Cristofolini et al. [32] defined an in vitro procedure to assess the long-term effect of most stressing activities on the integrity of hip implant cement mantle. This study concluded that the physiological load history presented is an effective compromise between an applicable test and realistic simulation of the patient's physical activities.

A. Roques et al. [33] investigated the degradation of cement mantle in vitro using AE as a passive experimental method by analyzing AE parameters using load level and aging method. In this study, AE online monitoring has been used to evaluate the performance of simulated artificial hip replacement constructs and their constituents during static and fatigue testing. This methodology could be used as a preclinical tool for assessing the integrity of cement loaded bearing implants.

In another reported work, Rowland et al. [34] introduced an improved technique of the metal-on-metal hip replacement and resurfacing to overcome stress shielding with the help of five station hip simulators (metal cup on metal head (MoM) hips during 3 million wear cycle). It is concluded that AE is effective in monitoring various active wear mechanisms of metal-on-metal hip, such as abrasion, grooving, adhesion, and surface fatigue and suggested further analysis of synchronized AE signal data obtained from head and cup movements.

Rodgers et al. [35] presented a combination of in vitro and in vivo studies, and comparison was drawn on the measurements of the acoustic signature created by a range of THR implant combinations. In vitro test set-ups include manual manipulation of implants as well as robot manipulation, where in vivo monitoring considers patients with audible squeaking, referred for revision surgery and patients who are interested in using an array of four passive ultrasonic receivers. A strong correlation between in vivo and in vitro testing is achieved by using implants retrieved during revision surgery of patients previously subjected to in vivo testing. In 2017, Fitzpatrick et al. [36] developed an AE monitoring prototype diagnostic device for the assessment of implant wear and stability of THR patients. Results indicate that the designed AE monitoring device is an effective diagnostic tool for the assessment of wear and tear of THR implants by extending over multiple days in normal life with more implants.

3.3 Crack detection

Crack detection is another important benefit of using AE. Li et al. [37] used AE techniques to investigate fatigue damage occurring in a cemented femoral stem of THR. This study proved that AE technique has the potential to be a preclinical tool to evaluate fatigue-induced damage to the cemented hip joint. In another work by Qi et al. [38] a three-dimensional testing model with real-time capability, AE is used to monitor cement microcrack formation in the cemented femoral stem. Yamada et al. [39] studied microdamages during compression tests in the ceramic femoral head for an artificial hip joint, which was monitored using AE technique. In this work, the finite element method (FEM) was used to compute the fracture strength and critical stress for main crack formation, and this study established crucial stress as a measure of fatigue strength. In another work by Yamada et al. [40], experiments were conducted to understand the behavior of alumina femoral heads used in hip arthroplasty under compression using AE technology. Schulman et al. [41] proposed a unique AE method to study the fatigue mechanism of total hip arthroplasty. In their study, AE data linked with the patterns of microcrack progression, particularly along the screw at an inferior location. The AE linear trend plot demonstrated similarity with respective actuator displacement vs. time curves. Wakayama et al. [42, 43] used AE monitoring for the detection of microdamages during the four-point bending proof test on alumina bioceramics. The results of all these assessments revealed that the increasing point of AE energy leads to the main crack formation that degrades the specimen strength.

Gueiral et al. [44] described the importance of identifying the location of AE sources for in vitro monitoring of THR by modeling and studying the origin, propagation, parameters, and detection of AE signals. The study stated that location of the AE source depends on the geometry of the structure and interfaces of the components. More AE sources are required if the structure is cylindrical or other irregular shape or geometry. Franke et al. [45] developed an adaptive AE measurement system named Bone Diagnostic System (BONDIAS) for non-invasive diagnosis of bone rupture and assessment of the tribological status of human femur and knee joint. Crack initiation and crack propagation can be assessed by this non-invasive diagnosis method. Schwalbe et al. [46] used resonant sensors to carry out AE analysis for human femur diagnosis and to know the cracking threshold, especially during the healing of bone after bone fracture and disease. The studies indicate that AE analysis of crack formation under load is identical for in vivo and in vitro experiments, and the broadband sensitive sensors are of great importance in medical diagnostics.

3.4 Progressive failure monitoring and location analysis

An in vitro AE testing [47] with directly embedded AE sensors within the cemented femoral stem construct determines its integrity during fatigue loading. Mavrogordato et al. [48] proposed a method where AE sensors can be directly embedded in the femoral stem of the implant, thereby reducing signal attenuation and eliminating potential complications and variability associated with fixing the sensor to the sample. This study reveals that embedded sensors are a feasible alternative to the standard sensors mounted externally in monitoring failure of a construct.

3.5 Fracture or damage characterization

In 2012, Stark et al. [49] conducted several uniaxial pressure tests on bones from different animal species including sheep (ovine), bulls (bovine), and pig (porcine) and on a processed, artificial bone mimicking human femur to investigate the capabilities of AE techniques in recording, localization, and characterization using high fidelity and multiresonant sensors. Strantza et al. [50] measured parameters like wave velocity, dispersion, attenuation, average frequency (AF), rise time over the maximum amplitude (RA), and central frequency (CF) using broadband AE sensors by mounting four sensors at small intervals on the surface of femur bone and to record the response after pencil lead break excitations. Strantza et al. [51] studied the behavior of AE obtained from eleven human femur specimens (excised from cadavers) during fracture due to flexural load. Test results reveal that load history correlates to the number of AE signals acquired and its amplitude. The damage characterization on human femur bones/tissues by ultrasonic and AE method investigations [52, 53] revealed that AE activity could be used in the identification of the onset of cracking that occurs much earlier than a macroscopic fracture or visible cracks and also provide more information on the fracture phenomena, very similar to ultrasonic. Since the principles of both techniques are different, careful consideration is required in analyzing the output variables and interpreting the damage mechanisms.

3.6 Structural symmetry

The THR structural symmetry or stability also can be monitored by AE methods. In 2003, Kwong et al. [54] developed an acoustical technique for evaluation of relative transmission of sound energy in both hip joints of a test subject for the measurement of structural symmetry of these hip joints. This study showed that acoustical technique delivers a practical method for structural testing of symmetry of hip bones by providing reliable information and offers a baseline data for further investigation into developmental dysplasia of the hip in neonates. Acoustic and vibration analysis technique (AVT) enabled analysis of subject-specific hip joint structural and mechanical conditions during in vivo weight-bearing activity [55]. In this study, in addition to acoustic signals, vibration signals were collected through an accelerometer (tri-axial) following gait kinematics of 5 THA subjects, while walking on a treadmill. In vivo kinematics and femoral head tribological movements were quantified through video-fluoroscopy are then correlated with acoustic and vibration data. The outcome showed that distinct variations between different subjects have existed with a good correlation of sound and vibration data. It seemed to be the first study to document and correlate visual effects with audible and vibration emissions of THR for examining the hip joint conditions.

3.7 Friction and noise

In THR monitoring, the friction and noise variation can be useful diagnostic tools. In 2003, Wierzcholski et al. [56] presented AE behavior corresponding to various kinds of friction forces generated in a human joint gap. The main factors that influence AE due to the friction forces by squeezing and weeping in macro, micro, and nano levels for porous cartilage and its corresponding analytical solutions are described in this work. Investigation of noise in ceramics bearing surfaces, a commonly recognized problem in THR, was reported by Iarovici et al. [57]. In 2012, Khan-Edmundson et al. [58] employ an AE prototype with four passive ultrasonic receivers in order to assess concept feasibility. A total of 45 patients were considered to determine the transfer function and attenuation properties between impulse sources and measured response at the sensors that lead to the determination of overall feasibility.

Gitis. N et al. [59] conducted hip-simulating tests with in situ monitoring tribological parameters of the metal head polymer cup (MoP) hip joint with bovine serum. AE signals were more sensitive to the presence of wear particles, and the friction torque is highly sensitive during break-in and pre-failure.

3.8 Routine/risk evaluation

Previous studies were also reported on a new cost-effective and non-invasive technique that can be routinely used for diagnostics of hip joint conditions. Glaser et al. [60] investigated the applicability of fluoroscopy for in vivo audible interactions and vibration propagation in 31 hip implants. Sound emissions and vibration at the hip joint interface are digitally captured and correlated with the kinematics of the hip joint obtained from fluoroscopy. Proposed work has great importance to surgeons and engineers to get valuable insight into the hip joint performance in an inexpensive and non-invasive manner. Itaro Morohashi et al. [61] introduced a method to objectively quantify the sound produced during stem insertion and investigated the relationship between these sounds and the occurrence of intraoperative fracture and postoperative subsidence. Results indicate the possibility of using acoustic evaluation to assess the risk of complications associated with cementless stems.

4 Progress in the usage of AE for the THR monitoring

Existing studies revealed that structural monitoring of THR by AE is a widely developing area in the field of orthopedic implant evaluation. It is also noted that AE has the potential to evaluate the structural integrity of THR implants irrespective of the material components. Load level testing for damage characterization varies in each work presented in the previous section. The implanted synthetic femur was placed under a bi-axial servo-hydraulic testing machine, in a study reported by Christofolini et al. [32]. From the results, it is evident that the highest values of elastic micro-movements correspond to the highest load-bearing activity. Progressive damage monitoring due to loading is performed in 9 stem constructs with 9 different tests [48]. And the embedded sensors with some challenges can be used in determining the integrity of cement mantle under static loading conditions.

Yamada et al. [39, 40] performed a compression test in the alumina femoral heads to determine microdamage and characterize the microfracture process using the AE technique. The micrograph of the fracture surface displayed the formation of microcracks with the rapid increase in cumulative AE energy. In this work, finite element analysis (FEA) is used to determine the stress and strain distributions of the femoral head, and thereby, critical stresses and fracture strength were determined.

Resonant frequency monitoring (RFM) as a non-invasive monitoring method for hip prosthesis integrity evaluation is verified in [27, 28]. Different experiments were conducted to evaluate the sound behavior of cow bone with different types of prostheses [27] and full metal endoprosthesis [28]. Animal model or human bone specimens were used for AE evaluation with respect to its frequency time–dependent behavior [49]. Structural symmetry measurement of normal human hips by AE techniques [54] offers a baseline for further study of hip disorders related to bone and joint symmetry.

Recent AE studies on the integrity assessment of the knee joint include a wearable system with a sound sensing and recording device. The framework is for AE evaluation on knee joint after musculoskeletal injury [62]. In this method, a wearable multimodal joint sound sensing device and a microphone were used to record the sound signals. To assess the integrity, the interaction between joint components during weight-bearing movement considers AE number of hits, which has the potential to serve as osteoarthritis biomarker [63]. AE pattern-recognition study with an acute knee injury with an unsupervised graph mining algorithm is depicted in work [62, 63]. AE signals were processed to extract its time and frequency domain features, and k-nearest neighbor graphs were constructed accordingly. Wearable system with microphones and electronics were used in the scheme that provides a biomarker relating to the knee joint health. In summary, the reported works reveal that AE has the potential to be a primary diagnostic tool in implant failure analysis. Table 1 illustrates AE signal features that address the presence of risk or complications associated with the sample THR implants. Also, it is observed that the competence of AE as an early diagnostic tool for THR implant monitoring requires further investigation and development to minimize the chances of secondary replacement surgery.

5 Future perspective

Structural health monitoring (SHM), such as NDT, performs monitoring of the structural integrity of materials when a material/structure is in its regular operation. Commonly used non-destructive testing (NDT) methods in the biomedical field are radiography, ultrasonic infrared evaluation, fiber optics, electromagnetic testing, eddy current evaluation, magnetic particle evaluation, vibration-based technique, and AE evaluation. All these schemes have one or more flaws associated when it comes to the biomedical field. The use of radiography is hazardous to health. Ultrasonic evaluations can detect a broader range of cracks but is not cost-effective and not efficient in detecting minute cracks. The same is the case with fiber optics and sonic infra-red evaluation. Internal flaw detection is not possible with techniques such as eddy current and electromagnetic testing. The vibration-based method mainly provides integrity information globally, so this scheme may fail to notice some problems occurring in large structures. In AE, elastic waves generated from a material when crack/failure/rubbing occurs, on the other hand, provide information both globally and locally. AE is cost-effective, non-invasive, harmless, no pain, time-efficient, no danger of infection, and health burden, and it is a non-destructive valuation technique. All these reveal the possibility of extending AE as an efficient evaluation technique in clinical applications, especially in orthopedic implants.

Despite these advantages, AE monitoring in hip implants is very much challenging when thinking about the efficacy of generating/capturing AE elastic waves from a highly complicated heterogeneous bone structure. Developing an optimized model for AE monitoring of THR should address different types of anatomy and biomechanics associated with each implant. Some of the potential limitations that may arise in this case is identifying a location to place these biosensors in each implant, transmit the captured elastic waves to the desired capturing devices such as smartphones, and also how tissues/muscles/neuro movements will accommodate the embedded sensors within the implant.

Current literature shows various methods in THR performance evaluation, including fatigue-induced damage, microcrack formation, microdamage, integrity evaluation, failure analysis, loosening detection, and fracture analysis.

Table 1 Reported research that involves AE technique in monitoring hip implants

Risk/complication	Implant material	Signal features	Results	Authors
Debonding/damage	Cemented components	Energy, amplitude	Earlier damage detection	M. Browne et al. [20]
Damage accumulation	Ceramic femoral head	Energy-finite element analysis	Microcrack detection	Y. Yamada et al. [34]
Fatigue failure	Acrylic bone cement	Duration, energy	Onset of critical damage	A. Roques et al. [27]
	Plate and screw system	Amplitude range and number of microcracks, actuator displacement	Better reveal the failure mechanism of the humeral fracture fixation	J. Schulman et al. [35]
Microcracks	Cemented femoral stem	Signal energy	microcrack source location	G. Qi et al. [32]
	Alumina bioceramics	AE energy, radius and nucleation velocity of microcracks	Quantitative detection of microcracks	S. Wakayama et al. [37]
	Human femur	Energy, frequency, signal duration, amplitude	Prediction of bone rupture and assessment of the tribological status	R. Franke et al. [39]
Microdamage	Bioceramics	AE energy	Increasing point of AE energy indicates main crack formation	S. Wakayama et al. [36]
Loosening	Bovine and human cadaver	Resonance frequency monitoring	Integrity monitoring and surface analysis	A. Paech et al. [21]
	Metal hip endoprosthesis	Frequency-resonance measurement	Monitor in-growth or loosening	A. Paech et al. [22]
	Normal, artificial hip joint	Frequency components	Early loosening detection	X.-J. Gao et al. [23]
	Cemented and cementless prosthesis	Resonance frequency monitoring	osteointegration surveillance and early detection of interface problems	A. Unger et al. [24]
	Porcine foreleg specimens	Frequency	Diagnose different loosening status of the custom implant	C. Ruther et al. [25]
Cracking and progressive damage	Stainless steel stems, cement mantle	Energy, rise time	Monitor progressive failure	M. Mavrogordato et al. [42]
Fracture	Femur specimens	Frequency, waveform shape parameters	Identification of onset of cracking	M. Strantza et al. [45]
	Femur specimens	Frequency, rise time	Onset of cracking, different modes of fracture	M. Strantza et al. [46], D. G. Aggelis et al. [47]
Coherence and discrepancy	Normal human hip	Relative intensity, frequency bands	Measure structural symmetry	K. S. Kwong et al. [48]
Degradation	Metal-on-metal, metal-on-plastic, ceramic-on-ceramic	Time, frequency domain responses	Monitor wear and degradation of TH implants	A. Khan-Edmundson et al. [52]
Wear	Ceramic-on-ceramic	Frequency	As a diagnostic tool for assessing THR implant condition	A. J. FitzPatrick et al. [30]

Existing studies and best practices reveal the necessity to develop an AE methodology to determine various impairment range levels that are highly acceptable with the challenges associated with hip implant monitoring such as early diagnosis of osteolysis and implant failures after the primary THR.

An intraoperative method to assess the initial stability or quality of the fixation of cementless acetabular implants suggested [64] forms a first step in the development of real-time, non-destructive, acoustic, and user-friendly measurement method. An extensive feature set-time features as well as frequency characteristics were assessed in this study. Analysis of resonance frequencies or response spectra helps to determine the quality of fixation of cementless implants, such as lack of implant stability.

In 2017, Rodgers et al. [65] employed three different event detection methods, such as statistical variation based on sound intensity, continuous wavelet transforms (CWT) event detection, and root-mean-squared (RMS) event detection in determining the condition of THR implants. Identifying the largest sound intensity from all the windows can be categorized as the most representative of acoustic events of interest. Wavelet analysis in this scheme considers a scale parameter and position parameter. Discontinuities in the signal are identified with respect to the large coefficient values at all values of the scale factor. The RMS value of the samples in each of the windows is calculated and stored in an array. These analyses were conducted in both in vivo and in vitro test set up and showed the effectiveness of AE in condition monitoring of THR implants.

The high-level architecture of the proposed scheme is depicted in Fig. 7. A wearable interrogator with a biosensor and recording device capture the AE signals. Pre-processing module, the first phase associated with this scheme, takes the captured AE signal as input and performs short-term processing, which manipulates the data appropriately. This assists in improving the results of analysis and synthesis. The pre-processed signal is transferred to the feature extraction module, where its computational characteristics are captured and given to the pattern-recognition module. Main parameters such as frequency components for early loosening detection, energy and rise time for the evaluation of onset of cracking, duration, and rise time for failure characterization and relative intensity towards structural symmetry determination are being considered. Pattern-recognition module, an equally important phase associated with this scheme, screens the extracted signal features and classify them appropriately to the THR Impairment range. The prospective scheme has phases similar to data collection, feature extraction, verification, and identification associated with the work [66, 67] but in the context of AE signal processing allied to THR implants.

6 Conclusions

This article introduces the field of acoustic emission (AE) and its practical application in the biomedical field, especially considering the works in THR surgery. Currently, there is no well-accepted diagnostic tool available for the early prediction of hip implant failures. Proper interpretation

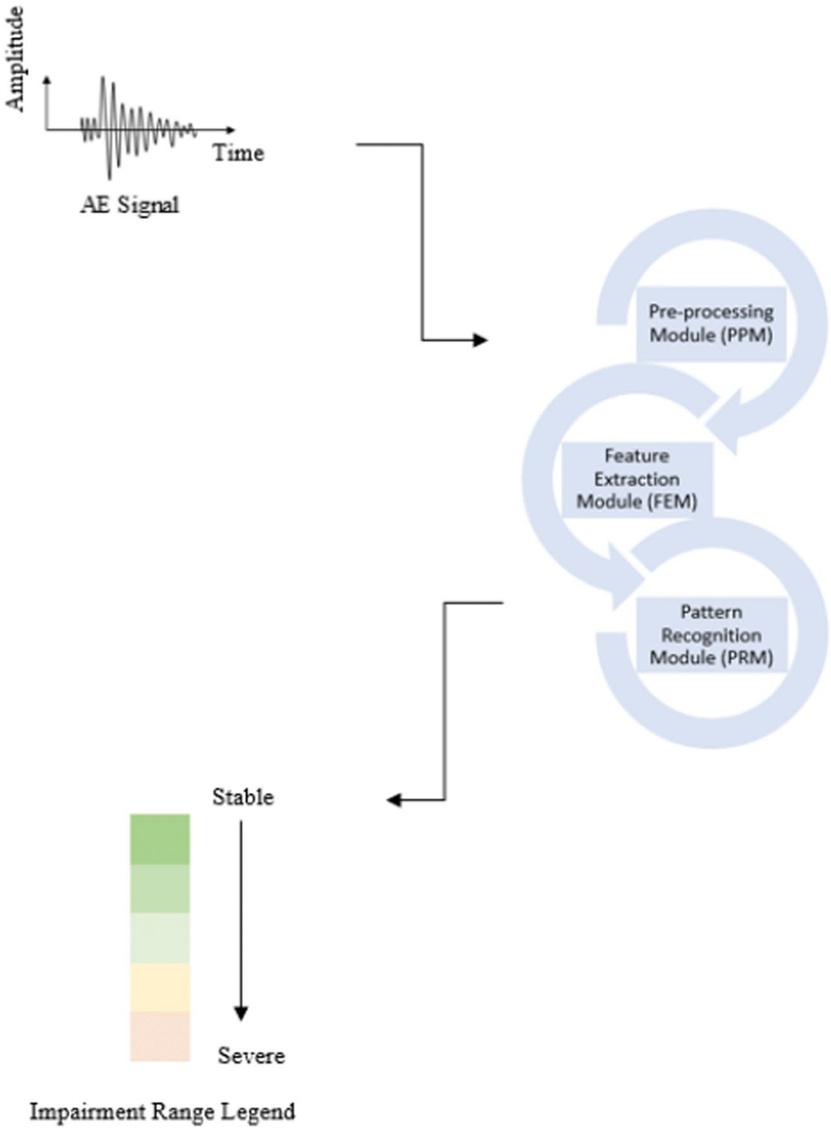

Fig. 7 High-level architectural diagram to demonstrate how the acoustic emission data could be useful to generate a clinical output

of AE data with accurate modeling mainly on its energy and frequency characteristics gives critical insights on originating events, probability of crack and fracture growth, risk of complications, and accurate and early loosening detection of any orthopedic implants. Improving the AE technique as a non-intrusive method in early detection of active damage mechanisms in the case of total hip replacement (THR) surgery and orthopedics research, in general, is challenging and critical. By solving the limitations of the reported works, AE technique has the potential to become a useful THR health-monitoring tool for the patients and surgeons.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

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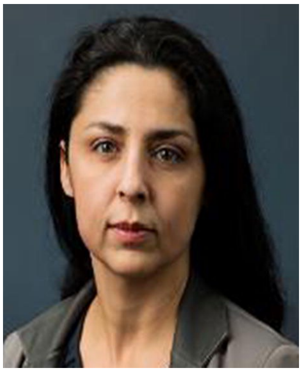

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