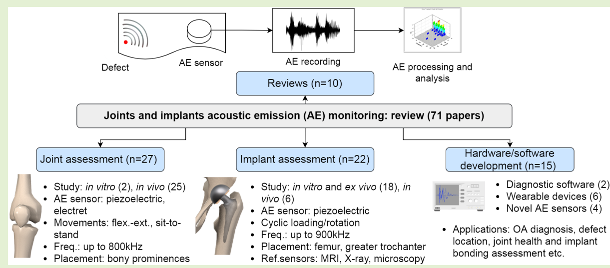
Assessment of Hip and Knee Joints and Implants Using Acoustic Emission Monitoring: A Scoping Review

Liudmila Khokhlova, Dimitrios-Sokratis Komaris, Salvatore Tedesco, *Member, IEEE*, and Brendan O'Flynn, *Senior Member, IEEE*

***Abstract*—Objectives: Population ageing and the subsequent increase of joint disorders prevalence requires the development of non-invasive and early diagnostic methods to enable timely medical assistance and promote healthy aging. Over the last decades, acoustic emission (AE) monitoring, a technique widely used in non-destructive testing, has also been introduced in orthopedics as a diagnostic tool. This review aims to synthesize the literature on the use of AE monitoring for the assessment of hip and knee joints or implants, highlighting the practical aspects and implementation considerations. Methods: this review was conducted as per the PRISMA statement for scoping reviews. All types of studies, with no limits on Articles were assessed and study design parameters and technical characteristics were extracted from relevant studies. Results: conducted search identified 1379 articles and 64 were kept for charting. Seven additional articles were added at a later stage. Reviewed works were grouped into studies on joint condition assessment, implant assessment, and hardware or software development. Native knees and hip implants were most commonly assessed. The most researched conditions were osteoarthritis, implant loosening or squeaking in vivo and structural damage of implants in vitro. Conclusion: in recent years, AE monitoring showed potential of becoming a useful diagnostic tool for lower limb pathologies. However, further research is needed to refine the existing methods and assess their feasibility in early diagnostics. Significance: The current state of research on AE monitoring for hip and knee joint assessment is described and future research directions are identified.**



***Index Terms*—Acoustic emission, joints, implant, medical diagnosis, orthopedics.**

I. Introduction

ACOUSTIC emission (AE) monitoring is a non-destructive testing technique, widely used to detect the presence of defects, and to locate their positions, in structures of various kinds [1]. AE monitoring is based on the recording of transient elastic waves generated within a material or structure due to the rapid release of energy from localized sources [2]. The AE signals may originate from mechanical or phase transformations, corrosion, friction, and magnetic processes within the material [3]. Since its first application in the early sixties, AE monitoring has become increasingly popular in the petrochemical, nuclear, aerospace and other industries [4], and is an actively researched topic with many applications, such as monitoring of fracture behavior and corrosion processes, material fatigue, leaks and faults detection [5].

A typical AE monitoring system (Fig. 1, top) takes its input from an AE sensor that converts dynamic surface motion into electric signals [6]. Due to the low amplitude of AE signals and the high impedance of piezoelectric sensors, the amplification is usually carried out in two steps, firstly by the pre-amplifier and subsequently by the main amplifier. Band pass filters are also employed to eliminate unwanted noise, such as sensor and electrical circuit noise, electromagnetic interference, background and technological acoustics noise. Whereas the conventionally used term «acoustic» is applied to sonic waves within the range of human hearing, «acoustic emission» refers to high frequency elastic waves in solids, and the filters' bandwidths can range from several kHz and up

Manuscript received 11 September 2020; accepted 7 December 2020. Date of publication 16 December 2020; date of current version 30 June 2021. This work was supported by the Science Foundation Ireland (SFI) under Grant number 12/RC/2289-P2 (INSIGHT) and in part under Grant numbers 13/RC/2077 (CONNECT) and 16/RC/3918 (CONFIRM) which are co-funded under the European Regional Development Fund (ERDF). The associate editor coordinating the review of this article and approving it for publication was Dr. Ravibabu Mulaveesala. *(Corresponding author: Liudmila Khokhlova.)*

The authors are with the Insight Centre for Data Analytics, Tyndall National Institute, University College Cork, Cork, T12 YT20 Ireland (e-mail: liudmila.khokhlova@tyndall.ie).

This article has supplementary downloadable material available at https://doi.org/10.1109/JSEN.2020.3045203, provided by the authors.
Digital Object Identifier 10.1109/JSEN.2020.3045203

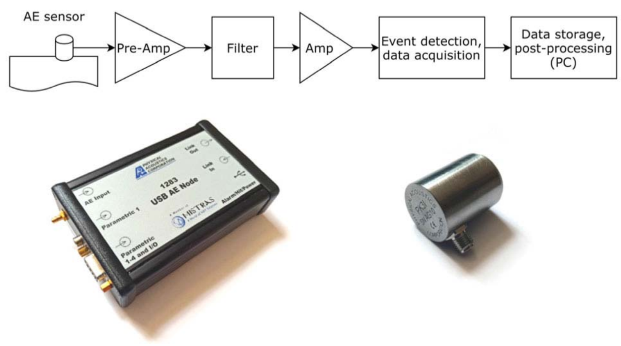


Fig. 1. AE monitoring system - flow-chart (top), Physical Acoustics data acquisition device (bottom left) and AE sensor (bottom right).

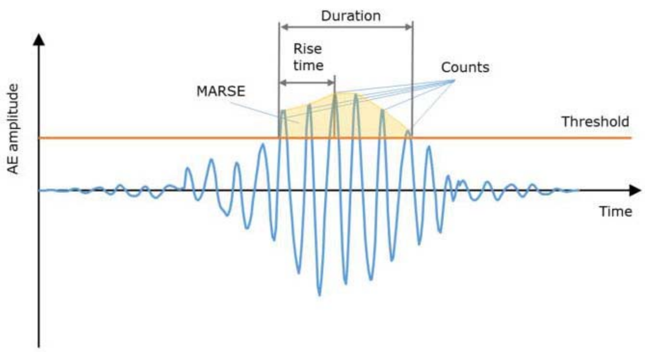


Fig. 2. Parameters of an AE signal.

to 1 MHz [6]. Following filtering, analog AE signals can then be converted into digital form and be post-processed. These components can be physically incorporated in to a monitoring system in functional blocks (Fig. 1, top) in various order, for example, the main amplifier, filters and analog-to-digital converter can be incorporated in a single data acquisition device (Fig. 1, bottom left), while the pre-amplifier can be embedded in the sensor (Fig.1, bottom right).

A variety of different approaches for signal analysis exist, but the most frequently used method is based on the registration of AE signals that exceed a preset or a floating amplitude threshold. Registered events are referred to as hits, and their characteristics, such as number of hits (counts), duration, rise and fall times, and measured area under the rectified signal envelope (MARSE) are commonly measured (Fig. 2). Specific values of such signal parameters can be an indication of existing defects in the material or formation of microcracks. More advanced methods of AE signal analysis include, for example, wavelet transform, moment tensor and 3D finite element analysis [1].

AE monitoring can be used for the investigation of the behavior of materials and structures under loads, wear and friction, phase transformation, stress corrosion and other material phenomena [1]. The fact that AE monitoring is non-invasive, without harmful side effects associated with radiation exposure, adds to its application in the medical field and particularly in orthopedics. Early works in the application of AE monitoring in orthopedics date back to the mid-seventies, in topics such as the study of AEs in bones during stretching and re-stressing [7], [8], bone fracture healing in dogs, and osteoporotic bone microstructure and implant behavior [9]. Even though AE monitoring in applied medicine has not been used as extensively as it is in industry [5], a number of studies recently indicated its utility in the assessment of joints due to cartilage and bone deterioration e.g. [10], [11], ligament rupture e.g. [12], [13] and implant loosening e.g. [14]. This renewed interest in medical AE monitoring for non-invasive diagnostics is associated with prevalence of degenerative joint disorders and the increased rate of joint replacement surgeries in recent decades; for instance, it is estimated that the lifetime risk of developing knee osteoarthritis is at 45% in the USA [15], while the risk of undergoing total knee arthroplasty (TKA) or total hip arthroplasty (THA) replacement is at 10% in the UK [16]. For example, as indicated by Kremers *et al.* [17], only in USA the prevalence of total hip and total knee replacement was 0.83% and 1.52% in 2010, accounting for more than seven million individuals living with artificial hips and knees. Moreover the rate of total joint replacements is likely to continue to increase in the coming decades [17], [18].

While several reviews on the topic in a wider context exist [19]–[21], a well-defined and transparent literature search, data charting and interpretation of findings were not attempted before. Considering the diverse nature of the existing literature, a scoping review was deemed as the most appropriate tool to map the research in this area [22], [23]. The research question posed seeks to determine the nature and extent of the current research in the use of AE monitoring for the condition assessment of human lower limb joints and implants. This scoping review aims to identify knowledge gaps and prospective research directions, and outline the challenges in the application of AE techniques in orthopedics and particularly in joint assessment. Up to date studies were analyzed and synthesized to present advancements in the field and the specifics of the experimental set ups, such as sensor placement, type of monitored activities, and the most indicative AE parameters for specific conditions.

II. Methods

The scoping review protocol was developed following the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines [24] and was registered in the OSF open registries network [25]. A comprehensive literature search was conducted in April 2020, using Embase, PubMed (incl. MEDLINE), and Web of Science electronic databases, and Google Scholar search engine. This set of databases is considered to provide sufficient recall, averaging at 98.3% for systematic reviews [26]. Database recommendations for systematic reviews should also provide sufficient recall for scoping reviews for journal articles and to ensure extensive coverage of the grey literature, Google Scholar search was additionally extended beyond the recommended 200 records for systematic reviews [15] to 600 in this review. While both PubMed and Embase include all MEDLINE records, differences in article indexing between databases

TABLE I
SEARCH STRINGS

Database/search engine	Search string
Embase	"acoustic* emission*":ab,kw,ti AND (knee:ab,kw,ti OR hip:ab,kw,ti OR bone:ab,kw,ti OR joint:ab,kw,ti OR ligament:ab,kw,ti OR cartilage:ab,kw,ti OR implant:ab,kw,ti OR prosthe*:ab,kw,ti) AND ([english]/lim OR [russian]/lim)
PubMed	"acoustic emission*" AND (knee OR hip OR joint OR bone OR ligament OR cartilage OR implant* OR prosthe*)
Web of Science	TS=(("acoustic* emission*") AND (knee OR hip OR joint OR bone OR ligament OR cartilage OR implant* OR prosthe*))
Google Scholar	knee OR hip OR joint OR bone OR ligament OR cartilage OR implant OR prosthesis "acoustic emission" -engine -freight -bridge -dental -speech -tank -military -wood -timber -pipeline -turbine -coal -gas -rock -welding -cable

may result in dissimilar outcomes, therefore, both databases were included [27]. Considering the review's aims, no limits on date of publication, source or study type were placed. The search was restricted to studies published in languages spoken by researchers (English and Russian). Title, abstract and keywords search was performed in Embase and Web of Science, and an "all fields" search was used for PubMed and Google Scholar.

Only studies focusing on the condition assessment of hip or knee joints and implants by means of AE monitoring were included, while works investigating material properties, such as damage propagation in bioceramics or bone cement, were excluded. Studies using sensors or filter frequencies below 1 kHz were also excluded, as this frequency range refers to vibroarthrography [28]. Search results included articles with the "acoustic emission" phrase, and at least one of the following search terms: knee, hip, bone, joint, ligament, cartilage, implant or prosthesis. Wildcards were used to account for spelling variations (e.g. prosthe*: prosthetic, prosthesis etc.). Frequently used terms in studies of industrial or non-orthopedic applications were excluded from Google searches (Table I). The first 600 Google Scholar records were sorted by relevance, and irrelevant papers were excluded based on their titles and short summaries.

All extracted records were imported into Mendeley citation manager to identify duplicates, and were then transferred to Rayyan, an online application for conducting systematic reviews [29]. Title and abstract screening were conducted by a single researcher (LK), and eligible articles were full-text screened. Uncertainties considering study selection and data extraction were resolved by consensus and discussion with the other authors. Finally, backward reference search was performed on the identified reviews on the topic, and all relevant studies were additionally included in this review.

As the scope and nature of the available evidence was not fully known in advance, data extraction tables were created as the records were screened and analyzed. During full text scanning, articles were divided according to their topic into four groups (joint assessment, implant assessment, hardware and software description, and reviews) and data-charting forms were developed to determine which variables to extract for each group. A single reviewer (LK) charted the data, and the findings for each category were summarized.

Articles on joint condition assessment were categorized based on the researched medical condition (e.g. osteoarthritis, age related deterioration, anterior cruciate ligament rapture), physical impact (e.g. mechanical load), and the experimental parameters of each study were logged (e.g. number and type of sensors, placement, frequency range, recorded AE parameters, joint movements, number and characteristics of participants). Similarly, implant assessment studies were documented, along with information on the applied loads, researched conditions (e.g. mechanical failure, squeaking, loosening), and the specimens' description for all in vitro studies. Technical characteristics (e.g. number and types of sensors, frequency range, output signal), applications and validation methods, where applicable, were reported for works on hardware and software in joint or implant assessment. Short descriptions of the included reviews, the identified knowledge gaps and indicated perspectives were reported narratively.

III. RESULTS

A. Literature Search

The search identified 1379 articles (Fig. 3). Duplicate studies were excluded, resulting in 1075 records. Titles and abstracts were reviewed as against the study's inclusion and exclusion criteria, identifying 103 articles at this stage. Eight records were excluded as full texts were not available and one additional record was excluded as the text was written in German. Three conference abstracts, letter and two journal articles [30], [31] were excluded due to limited information being available in respect to the charted parameters of this review. Out of 103 articles, 64 were deemed as relevant during full text screening and were kept for charting (Fig. 3). Two additional newly published papers were identified from Google Scholar alerts and added on a later stage. Reference lists from all the selected review papers were scanned and five additional articles were included, totaling in 71.

B. Joint Assessment

Twenty-seven records focused on joint assessments (Supplemental materials: Tables III, IV), of which twenty-six assessed the condition of knees, and one evaluated both hip and knee joints [32]. A number of different medical conditions and their relation to AE signals were investigated (Table II): the most researched one was osteoarthritis (OA) with thirteen identified records, followed by age-related joint deterioration with six works. The effects of juvenile idiopathic arthritis (JIA), meniscal injury and surgery, and past knee injury or pain joint were also explored on a single publication each. AE signals during anterior cruciate ligament (ACL) rupture under strain were described in [12], [13]. Studies also examined AEs in relation to non-pathological joint conditions such as mechanical loads during movement [33], joint friction [34], the consistency of subject's joint acoustical signals between measurements [34], [35] and stride detection using AE during walking [36]. Only five studies conducted experiments ex vivo (Supplemental materials: Table III). Human cadaveric knee

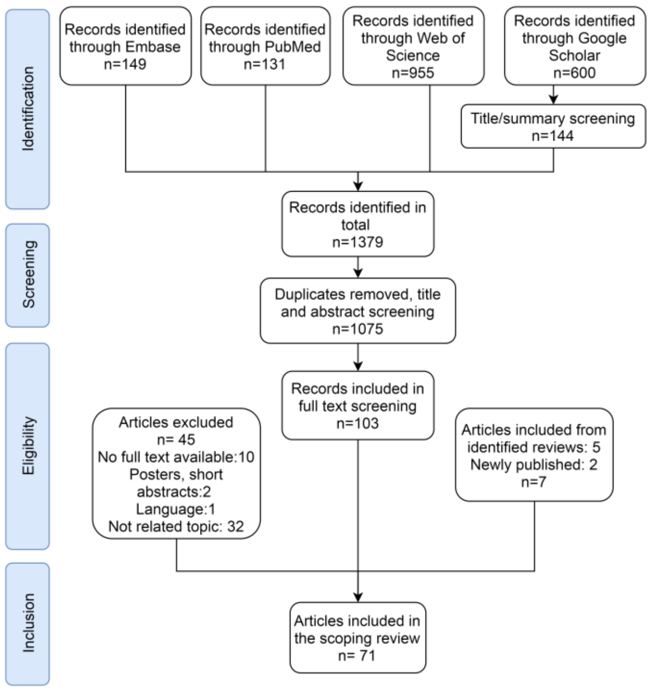


Fig. 3. Parameters of an AE signal.

specimens with all soft tissues removed except ACL were used in two studies [12], [13]. Meniscal tear, imitation of swelling by injecting saline solution and meniscectomy were performed on human cadaver limbs and their relation to AE during joint movement were investigated in [53]. Samples of hip and knee joint cartilage surfaces were used in [32] to evaluate surface roughness, while AE measurements were performed only in vivo, in participants with varying degree of cartilage deterioration. Femurs condyles pressed against polymeric counterparts simulating the tibial plateau were used in [34] to detect AEs caused by joint friction.

Sensors with a frequency range of up to 800 kHz were used in joint condition assessment [12], [13] (Supplemental materials: Table III). In the majority of the included studies, off-the-shelf or custom made piezoelectric (PE) sensors were used to obtain AE signals, however, other types of sensors such as MEMS e.g. [35], electret microphones e.g. [52] and accelerometers e.g. [50] were also utilized (Supplemental materials: Table III). Sensors were usually placed on the areas of bony prominences, such as the patella or the tibia and femur condyles. Regular medical tape was commonly used to fixate sensors on the skin, and a suction cup was used in [49]. Medical ultrasound gels [40], [42]–[45], [49], Vaseline [37] or wax [47] were routinely used to ensure optimal acoustic coupling. The number of sensors varied from one to four per knee (Supplemental materials: Table III). A wide variety of sensors' position on the knee was explored in the reviewed studies (Fig. 4). For the hip joint, sensor positioning was less diverse and was limited in the femoral bone prominences [54], greater trochanter area [55], or in the area from the iliac crest to the upper or mid femur in for studies with several using multiple sensors [56]–[59].

TABLE II
RESEARCHED JOINT CONDITIONS

Conditions	References	Number of studies
OA and rheumatoid arthritis	[10], [32], [36]–[46]	13
Age-related deteriorations	[10], [11], [44], [47]–[49]	6
JIA	[50], [51]	2
Knee injury/surgery	[52]	1
AE consistency	[34], [35]	2
Mechanical load	[33]	1
Meniscal injury/surgery	[53]	1
ACL rupture	[12], [13]	2
Instances of pain	[47]	1
Stride detection	[36]	1
Joint friction	[34]	1

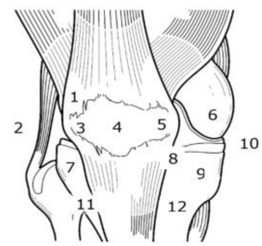


Fig. 4. Sensor placement: 1) lateral femur condyle: [44], [49]; 2) lateral side of the knee: [39]; 3) lateral side of the patella: [33], [35], [45]; 4) center of the patella: [11], [36], [46]; 5) medial side of the patella: [33], [45], [51], [52]; 6) medial femur condyle: [11], [38], [44]; 7) lateral tibia condyle: [11], [44], [46]; 8) inferior to patella and anterior to medial patella retinaculum: [37], [40]–[43], [60]; 9) medial tibia condyle: [11], [44], [46]; 10) medial side of the knee: [39]; 11) lateral to patellar tendon: [53]; 12) medial to patellar tendon: [50], [53].

Knee angles were commonly measured along with AE, using electrogoniometers (EG) or inertial measurement units (IMUs), while MRI scans and radiography were deployed as a reference method for assessing joint condition (Supplemental materials: Table III). To generate AE in vivo, different movements were performed by participants; sit-to-stand-to-sit (STSTS) and flexion-extension in sitting position (F/E) were used in the majority of the studies, whereas walking and squats or knee-bends were less common (Supplemental materials: Table III). A leg press machine was also employed in one study [33], and a variety of everyday activities including cycling were used in [34]. Considering the AE parameters of interest, authors focused on AE hits and their characteristics (number, amplitude, energy etc.), and waveform analysis (e.g. frequency distribution, signal patterns) (Supplemental materials: Table III).

C. Implant Assessment

Implants and their components (e.g. femoral heads) were assessed in 22 works (Supplemental materials: Table V, VI). The majority of the identified studies investigated hip implants, whilst only three articles [61]–[63] described knee assessments. Squeaking of hip implants was the most frequently addressed issue and was investigated in seven works, both *in vitro* and *in vivo*. Other conditions included material fatigue and accumulated damage under loads [64] or compression [65], including microcracks formation e.g. [66], wear [67], loosening or debounding of cement-retained implants [14] (Supplemental materials: Table VI).

Piezoelectric sensors were used to register AEs in all of the identified works. The sensors' operation frequency ranged from as low as 0.5Hz - 15 kHz [68] to the much higher bandwidth of 200 - 900 kHz [69]. The number of used sensors ranged from one to eight (Supplemental materials: Table V). Similar to the joint assessment *in vivo*, different movements were recorded to produce AEs, and various types of mechanical loads were used *in vitro*. Most commonly (in half of the *in vitro* studies), implants were subjected to cycling loading and compression. In [70] a pendulum strike was used and in [56], [68], [71] the implants were rotated manually or with robotic arms to produce squeaking. For *in vivo* implant assessments, walking was employed in eight out of nine studies, whereas squats/crouches, stair ascent/descent and STS were less popular (Supplemental materials: Table V).

Microscopy, radiography and ultrasound scanning were employed as reference methods of damage assessment (Supplemental materials: Table V). Video-fluoroscopy was used in [54], [72] to allow a direct association of the registered AEs to joint movement. Surface strain was measured by digital image correlation cameras in [62], [63]. Additional movement data were gathered using accelerometers and a force plate in [54] and a finite element analysis was also used as an alternative validation tool in [62].

Cadaver limbs were used in one study [70] and synthetic specimens (fiber glass or other composite artificial bone with implanted joint prosthesis) were used in 12 studies. For *in vitro* studies sample size did not exceed twenty specimens, whereas *in vivo* seven out of nine studies (Supplemental materials: Table V) had more than twenty participants with a maximum of 98 [55]. The recorded and processed AE parameters were similar to those used in joint assessment, focusing on AE hits parameters, whereas two works looked into specific signal waveforms [55] and spectral characteristics, such as primary frequency, frequency content etc. [58] (Supplemental materials: Table V).

D. Works Describing Hardware and Software

Fifteen works described devices and software for AE monitoring in the context of joint assessment (Supplemental materials: Table VII). Four articles [73]–[76] introduced novel AE sensors with thermosensitive elements to enhance the sensors' sensitivity. An audio-visual environment for multimodal AE analysis of the knee's condition was presented in [77]; the system provided a comparative analysis of two joints by using the animated movements of knees as reconstructed from 3D MRI, synchronized sonified AEs and visualized joint contact areas. A software for AE analysis (3DMem) was presented in [78], designed to investigate the cement's microcrack formations in femoral stems and visualize their location and distribution.

A stationary system for joint acoustic analysis was discussed in [40] and wearable devices for the evaluation of the knee's health were described in [35], [79]–[82]. While all the identified devices and sensors were intended for joint condition assessment, some specific applications were mentioned, such as AE source detection [74], tribological condition evaluation and prediction of femur rupture [81], osteoarthritis evaluation [75], [76], injury monitoring [35], [83], and quantifying rehabilitation stage [79]. Only one work specifically designed a system for hip implant condition assessment [56].

The use of adhesive patches and tapes was the main method of sensor attachment; however, in [35] authors suggested a knee "sleeve" design for future devices, whilst bandages were used in [56]. Works describing devices for knee condition assessment suggested the placement of sensors on the patella area (Supplemental materials: Table V), sensors of the device for hip implant condition assessment were placed from iliac crest to upper femur [56]. Knee angles were frequently measured along with AE by means of electrogoniometers in stationary systems [40] or IMUs in wearable solutions. A temperature and a lower-rate electrical bioimpedance measurement were also included in [82] to provide complex knee assessment, including swelling, activity level, and joint angle.

Authors frequently used off-the-shelf data acquisition hardware, such as the AE PCI-2 board (Physical Acoustic), myRIO (National Instruments) and Biopac modules, whereas custom made hardware were employed in [79], [81]. In stationary systems, the JAAS [40] and BoneDias [81] piezoelectric sensors were employed, whereas the wearable solutions presented in [35], [79]–[81] used microphones. Different types of sensors, such as MEMSs and contact electret microphones, were assessed in [83], [84] in order to determine the most suitable option for wearable applications. Filtered, but otherwise unprocessed acoustic signals were found to be the most frequent output of the developed hardware systems, however, four systems additionally recorded other parameters, such as the number of hits [35], [40], [80], [83].

E. Reviews

Ten review papers were identified. A short narrative review [9] was the earliest work touching the subject of non-destructive techniques for the evaluation of implant performance. A later work [85] provided an extensive overview of the general principles of AE monitoring and its application in the analysis of biomaterials, tissues and tissue/biomaterial interfaces, with a particular focus on detection sensitivity, signal analysis, relation of AE signals to microstructural phenomena and failure mechanisms. Three review papers provided descriptions of different methods of human joint monitoring, including AE analysis: a generic view on joint assessment was presented in [86], while more specific applications, such as monitoring of bone-implant interfaces and implant loosening were discussed in [87] and [88], respectively. An overview of potential biomarkers for knee OA was outlined in [10]. Narrative reviews, fully dedicated to acoustic emission techniques in orthopedics, were presented in [19]–[21], with [21] focusing on current and potential uses of AE monitoring in tribological assessments (i.e. joint wear and friction) and [20] on the evaluation of hip replacement constructs. The latest review [89] in the field of hip implant performance prediction by acoustic techniques covered this relatively narrow topic.

IV. Discussion

The reviewed studies in joint assessment showed positive results (Supplemental materials: Table IV), preliminary confirming the feasibility of using AE monitoring for distinguishing conditions such as OA e.g. [60], age-related deterioration e.g. [11], and trauma [53]. However, only one *in vivo* study [50] compared joints' AEs before and after an intervention (successful treatment of JIA). The majority of the included studies were pilot or small-scale validation and proof-of-concept works, with 16 out of 24 works including 10 or less participants/specimens per researched group. Given the emerging topic of AE in medicine, authors focused on the description of AE signals to specific conditions, thus indicating the potential use of AE monitoring as a diagnostic tool. However, using AE monitoring for diagnosis prior to the active clinical manifestation of the symptoms has yet to be reported.

Knee joints were more frequently researched than hip joints, most likely due to the higher acoustic wave attenuation from the soft tissues that lay between the hip joint and the sensors. The opposite trend was observed in implant condition assessment; since audible squeaking could be a sign of underlying defects in hip implants, seven studies (Supplemental materials: Table VI) investigated this phenomenon and the mechanisms behind it, in an effort to improve implant design. However, further research into the applications of AE monitoring in knee implant assessment could be expected, considering the higher prevalence of TKAs compared to THAs [17]. Contrary to joint assessment, AE monitoring in implants (Supplemental materials: Table VII), particularly *in vitro*, seems more promising in distinguishing minor changes in implant structure, such as microdamage [65], microcracks [90] and debounding [63]. Experiments *in vitro* are easily replicated and they can be adopted for newly developed implant designs to predict their performance *in vivo* and evaluate possible defects, such as cement microcracks [78], [91].

Regarding the hardware development for joint assessments *in vivo*, researchers either developed stationary diagnostic systems intended to be used in clinical settings, such as the JAAS [40] and BoneDias [81], or suggested potential solutions for wearable versions capable of remote or long-term monitoring e.g. [35]. For the *in vitro* assessments, the majority of the studies used commercially available AE equipment originally designed for industrial applications, without indicating the need for the development of specific sensors for human studies.

A. Sensors Placement, Type and Fixation

Sensor placement, particularly *in vivo*, is one of the key factors in the quality of the signal since appropriate positioning reduces movement artifacts and facilitates signal transmission from the source of the AEs to the skin surface. Sensors should be placed on a boney surface, like the patella or the tibiofermoral condyles, minimizing the acoustic wave's attenuation by soft tissues. In [11], the authors compared four sensor positions on the knee and concluded that sensors on the medial tibia condyle offered minimal muscular and dynamic artifacts for STSTS movements. The same sensor position should also be suitable for a range of movements with minimal knee abduction or rotation.

Sensor fixation is also critical, since tape or straps can generate acoustic emissions when deforming during movements. Yet, none of the reviewed works investigated the potential adverse effects of sensor fixation and how to address them. Contact sensors with coupling gels were most often used, since they facilitate acoustic signal transition from the skin surface to the sensor. At the same time contact sensors are quite susceptible to movement artifacts, and non-contact microphones were suggested as an alternative for wearable solutions. A recent study also concluded that non-contact microphones can be successfully used in either silent or loud background settings with sufficient repeatability [80].

B. Loading and Movements

During experiments on implants *in vitro* or *ex vivo*, mechanical equipment was used to apply loads or to recreate movements naturally occurring *in vivo* [14], [56], [57]. While providing excellent repeatability, loading equipment can introduce additional vibrations and AEs into the recorded signal, necessitating the presence of appropriate damping [57]–[59]. Manual manipulation was used as a non-vibrating alternative (e.g.[59], [58]), however, it does not necessarily provide better stability and movement repeatability. Even though a wide range of movements can be performed to trigger AE *in vivo*, no recommendations were made as to which tasks are optimal for clinical assessments. According to [43], the descending deceleration phase of the stand to sit movement is potentially the most discriminative for quantitative analyses and the monitoring of the knee's ageing and condition; however, only the STSTS task was considered in this study. The STSTS was in general the most commonly recorded activity for joint assessment (11 studies out of 27), yet, such movements exploit the participant's own weight as a load, which may be undesirable in joint condition evaluation since AEs and applied loads are correlated [33]. Therefore, evaluation with AEs can lead to false positive results in obese participants, particularly in the frequently researched pathologies, such as in OA, that are associated with obesity [92]. Alternative tasks with controlled loads and standardized movements, such as leg presses or cycling, should be considered.

C. AE Parameters and Analysis

It is suggested in [56] that tissue attenuation plays a significant role in AE analyses due to the high and low frequency signals being almost non-distinguishable from each other when recorded on the skin surface. In [58], AE signals were present throughout the whole frequency range of the recordings and reaching up to 50kHz, but signal amplitudes were lower for high frequency signals. Even though tissue attenuation was not specifically investigated in knees, fourteen studies (Supplemental materials: Table III) successfully registered signals with the lower band of the frequency range no higher than 35 kHz. Whereas some studies recorded frequencies up to 500 kHz [47], [60], in the majority of the joint assessment studies, frequencies did not exceed 200kHz. In implant assessments *in vitro*, the sensors' frequencies were significantly higher and reaching up to 2MHz [69] thanks to the absence of soft tissues and the high coupling quality between sensors and testing surface. Also, high signal sampling rates are also required, which cannot always be implemented. Optimal choice of frequency range was not specifically investigated, however squeaking is commonly recorded and analyzed in a lower bandwidth range, whereas damage and crack formation in a higher one.

The number of hits is a widely reported metric in non-destructive testing, but technical parameters such as the hits' threshold and frequency range are specific to each application. While the threshold's value is a determining factor for AE recordings, it is mostly not reported e.g. [45], [61]; however, the amplification of the AE signal in different hardware can be drastically altered, which in turn results in a variety of thresholds. Full reporting on the system's configuration, including levels of amplification, can be useful in determining the optimal parameters and standard procedures for AE monitoring. Among the other frequently reported metrics, the maximum amplitude distribution, percent occurrence and concentrated distribution of AE hits were considered as optimal biomarkers of OA and other conditions [45], [68]. Frequency distribution analysis (e.g., using Fourier transformation) [46], waveform analysis [54], [61], wavelet transformation [58], [69] or cestrum analysis [31] were also employed for AE joint assessment.

AE monitoring in industrial applications is commonly utilized to detect the location of defects or damage, but due to complicated heterogeneous structure of joints and implants, this prospect is still relatively unexplored in clinical AE monitoring. To date, only one group presented experimental studies [64], [66] and software [78] for microcracks location and visualization in synthetic femurs with cemented prosthesis. In the work by [69], AE bursts were also shown to indicate the location of a possible crack. Difficulties in accurately tracing microcracks arise from the complex composite structure of bone and implants that requires multiple sensors and high computational power. Determining the location of microcracks *in vivo* can be considered to be extremely difficult due to soft tissue attenuation, signal dispersion and discrepancies in joint structures among subjects.

D. AE Monitoring Limitations and Future Research Directions

Contrary to industrial applications, wave attenuation, dispersion functions and tribological characteristics are considerably more complex in heterogeneous organic structures such as joints, limiting the application of AE monitoring, particularly *in vivo*. Development of tissue attenuation models and wave propagation functions for complex structures and soft tissues may aid in addressing these issues in future. Furthermore, considering that AE in non-invasive, *in vivo* monitoring can only be triggered during movement, the problem of motion artifacts becomes significant. Additional studies are necessary to determine optimal sensor design, placement and fixation methods to resolve this issue. In addition, potential biomarkers and associated AE signal parameters, remain one of the most explored topics in AE clinical monitoring, yet they still need refinement and further clarification in the context of specific joint disorders.

The feasibility of AE monitoring to distinguish between healthy and pathological joints is well established, but early diagnosis or the identification of asymptomatic conditions remains unexplored. Cartilage defects location *in vivo* based on correlations of AE and contact surfaces change during movement can be considered another promising researched direction that can lead to new insights in OA development and substitute to a degree the expensive methods of diagnostics such as MRI.

Considering the analyses *in vitro*, the effectiveness of AE in implant's condition monitoring was established by multiple works (Supplemental materials: Table VII); however, the AE technique in determining defect locations in implants is still significantly lags behind successful industrial methods. Apart from complex structure of researched objects, additional difficulties in processing are also emerging from the high sampling rate and computational power which are necessary for a successful analysis.

E. Limitations of the Review

The present scoping review has some limitations that should be considered when interpreting the results. As opposed to industrial applications, research on AE emission in medical applications has yet to adopt a standardized terminology, thus relevant studies might not have been covered if authors used terms other than «acoustic emission». Additionally, animal studies, studies on assessment of materials for implants or bones, and closely related methods such as vibroarthrography and resonant frequency monitoring were excluded. In addition, the researchers were unable to obtain full texts of several papers. Another limitation arises from the absence of a quality assessment of the included studies; to achieve a high coverage on the topic, all relevant studies were included. However, recommendations, widely used practices and the obtained results of a wide range of studies were analyzed and reported in this review, making this work useful for a wide variety of researchers in the field of clinical AE monitoring.

V. Conclusion

This study presents an overview on the existing research on the use of AE techniques for human lower limb joints and implants' assessment *in vitro* and *in vivo*, as well as the current and prospective research directions and knowledge gaps in the field. AE monitoring for implant evaluation was first used more than thirty years ago but modern advances in electronics and increasing prevalence of joint disorders renewed the interest in the technique. While implant assessment remains closely related to material testing in industry, a whole new area of *in vivo* joint and implant diagnostics emerged, which may lead in the future to the early diagnosis of pathologies or to a wide range of applications in orthopedics.

Future research directions might include further investigations of AE propagation mechanisms in soft and bone tissues, development of mathematical models thereof, development of possible biomarkers for a range of joint conditions, design of sensors specific for *in vivo* applications, and refinement and standardization of AE monitoring procedures.

References

[1] K. Ono, "Acoustic emission in materials research—A review," *J. Acoustic Emission*, vol. 29, pp. 284–308, Jan. 2011.

[2] *Standard Terminology for Nondestructive Examinations*, Standard E1316, ASTM, 2011.

[3] K. Ono, "Acoustic emission," in *Handbook of Acoustics*, T. D. Rossing, Ed. New York, NY, USA: Springer, 2014, pp. 1209–1229.

[4] C. B. Scruby, "An introduction to acoustic emission," *J. Phys. E, Sci. Instrum.*, vol. 20, no. 8, p. 946, 1987.

[5] S. Gholizadeh, Z. Leman, and B. T. H. T. Baharudin, "A review of the application of acoustic emission technique in engineering," *Struct. Eng. Mech.*, vol. 54, no. 6, pp. 1075–1095, Jun. 2015.

[6] M. Ohtsu, "Sensor and instrument," in *Acoustic Emission Testing*, C. U. Grosse, Ed. Berlin, Germany: Springer, 2008, pp. 19–20.

[7] I. V. Knets *et al.*, "Acoustic emission in human bone tissue upon lengthwise stretching, Mekh." *Polim*, vol. 4, pp. 685–690, Jan. 1975.

[8] U. E. Krauya and Y. A. Lyakh, "Acoustic emission in restressing human bone tissue," *Polym. Mech.*, vol. 14, no. 1, pp. 91–94, 1978.

[9] J. L. Katz, "Engineering criteria for biomaterials: Some thoughts on *in situ* measurements," *Biomater., Med. Devices, Artif. Organs*, vol. 7, no. 1, pp. 81–87, Jan. 1979.

[10] L. Spain *et al.*, "Biomarkers for knee osteoarthritis: New technologies, new paradigms," *Int. J. Clin. Rheumatol.*, vol. 10, no. 4, pp. 287–297, Aug. 2015.

[11] T. I. Khan and H. Yoho, "Integrity analysis of knee joint by acoustic emission technique," *J. Multimodal User Interfaces*, vol. 10, no. 4, pp. 319–324, Dec. 2016.

[12] D. G. Aggelis *et al.*, "Rupture of anterior cruciate ligament monitored by acoustic emission," *J. Acoust. Soc. Amer.*, vol. 129, no. 6, pp. EL217–EL222, Jun. 2011.

[13] N. K. Paschos *et al.*, "An acoustic emission study for monitoring anterior cruciate ligament failure under tension," *Exp. Mech.*, vol. 53, no. 5, pp. 767–774, Jun. 2013.

[14] J. P. Davies, M.-K. Tse, and W. H. Harris, "Monitoring the integrity of the cement—Metal interface of total joint components *in vitro* using acoustic emission and ultrasound," *J. Arthroplasty*, vol. 11, no. 5, pp. 594–601, Aug. 1996.

[15] L. Murphy *et al.*, "Lifetime risk of symptomatic knee osteoarthritis," *Arthritis Care Res., Off. J. Amer. College Rheumatol.*, vol. 59, no. 9, pp. 1207–1213, Sep. 2008.

[16] D. J. Culliford *et al.*, "The lifetime risk of total hip and knee arthroplasty: Results from the UK general practice research database," *Osteoarthritis Cartilage*, vol. 20, no. 6, pp. 519–524, Jun. 2012.

[17] H. M. Kremers *et al.*, "Prevalence of total hip and knee replacement in the united states," *J. Bone Joint Surg. Amer. Volume*, vol. 97, no. 17, pp. 1386–1397, Sep. 2015.

[18] J. A. Singh, S. Yu, L. Chen, and J. D. Cleveland, "Rates of total joint replacement in the united states: Future projections to 2020–2040 using the national inpatient sample," *J. Rheumatol.*, vol. 46, no. 9, pp. 1134–1140, Sep. 2019.

[19] R. A. Kapur, "Acoustic emission in orthopaedics: A state of the art review," *J. Biomech.*, vol. 49, no. 16, pp. 4065–4072, Dec. 2016.

[20] M. Browne, A. Roques, and A. Taylor, "The acoustic emission technique in orthopaedics—A review," *J. Strain Anal. Eng. Des.*, vol. 40, no. 1, pp. 59–79, Jan. 2005.

[21] K. A. Olorunlambe, D. E. T. Shepherd, and K. D. Dearn, "A review of acoustic emission as a biotribological diagnostic tool," *Tribol. Mater., Surf. Interfaces*, vol. 13, no. 3, pp. 161–171, Jun. 2019.

[22] M. D. J. Peters, C. M. Godfrey, H. Khalil, P. McInerney, D. Parker, and C. B. Soares, "Guidance for conducting systematic scoping reviews," *Int. J. Evidence-Based Healthcare*, vol. 13, no. 3, pp. 141–146, Sep. 2015.

[23] H. L. Colquhoun *et al.*, "Scoping reviews: Time for clarity in definition, methods, and reporting," *J. Clin. Epidemiol.*, vol. 67, no. 12, pp. 1291–1294, Dec. 2014.

[24] A. C. Tricco *et al.*, "PRISMA extension for scoping reviews (PRISMA-ScR): Checklist and explanation," *Ann. Internal Med.*, vol. 169, no. 7, pp. 467–473, Oct. 2018.

[25] L. Khokhlova. *Hip and Knee Joint Assessment Using Acoustic Emission: A Scoping Review Protocol*. Accessed: May 6, 2020. [Online]. Available: https://osf.io/45uyg

[26] W. M. Bramer, M. L. Rethlefsen, J. Kleijnen, and O. H. Franco, "Optimal database combinations for literature searches in systematic reviews: A prospective exploratory study," *Syst. Rev.*, vol. 6, no. 1, p. 245, Dec. 2017.

[27] A. Y. Gasparyan, A. Y. Gasparyan, L. Ayvazyan, and G. D. Kitas, "Multidisciplinary bibliographic databases," *J. Korean Med. Sci.*, vol. 28, no. 9, pp. 1270–1275, Sep. 2013.

[28] R. E. Andersen, L. Arendt-Nielsen, and P. Madeleine, "A review of engineering aspects of vibroarthography of the knee joint," *Crit. Rev. Phys. Rehabil. Med.*, vol. 28, nos. 1–2, pp. 13–32, 2016.

[29] M. Ouzzani, H. Hammady, Z. Fedorowicz, and A. Elmagarmid, "Rayyan—A Web and mobile app for systematic reviews," *Syst. Rev.*, vol. 5, no. 1, p. 210, Dec. 2016.

[30] P. J. Gregson and M. Browne, "Lifetime predictions for orthopaedic implants," *Key Eng. Mater.*, vols. 204–205, pp. 383–394, Apr. 2001.

[31] A. J. FitzPatrick, G. W. Rodgers, T. B. F. Woodfield, and G. J. Hooper, "Cepstrum analysis for determining the fundamental frequency of total hip replacement acoustic emissions," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 9932–9937, Jul. 2017.

[32] K. Wierzcholski, "Acoustic emission diagnosis for human joint cartilage diseases," *Acta Bioeng. Biomech.*, vol. 17, no. 4, pp. 139–148, Jan. 2015.

[33] H.-K. Jeong, M. B. Pouyan, D. C. Whittingslow, V. Ganti, and O. T. Inan, "Quantifying the effects of increasing mechanical stress on knee acoustical emissions using unsupervised graph mining," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 3, pp. 594–601, Mar. 2018.

[34] H.-J. Schwalbe, G. Bamfaste, and R.-P. Franke, "Non-destructive and non-invasive observation of friction and wear of human joints and of fracture initiation by acoustic emission," *Proc. Inst. Mech. Eng. H, J. Eng. Med.*, vol. 213, no. 1, pp. 41–48, Jan. 1999.

[35] H. Toreyin, H. K. Jeong, S. Hersek, C. N. Teague, and O. T. Inan, "Quantifying the consistency of wearable knee acoustical emission measurements during complex motions," *IEEE J. Biomed. Health Informat.*, vol. 20, no. 5, pp. 1265–1272, Sep. 2016.

[36] C. Yiallourides, V. Manning-Eid, A. H. Moore, and P. A. Naylor, "A dynamic programming approach for automatic stride detection and segmentation in acoustic emission from the knee," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, New Orleans, LA, USA, Mar. 2017, pp. 401–405.

[37] D. K. Schlüter *et al.*, "Use of acoustic emission to identify novel candidate biomarkers for knee osteoarthritis (OA)," *PLoS ONE*, vol. 14, no. 10, Oct. 2019, Art. no. e0223711.

[38] J. Kiselev, B. Ziegler, H. J. Schwalbe, R. P. Franke, and U. Wolf, "Detection of osteoarthritis using acoustic emission analysis," *Med. Eng. Phys.*, vol. 65, pp. 57–60, Mar. 2019.

[39] A. Tiulpin, J. Thevenot, J. Hirvasniemi, J. Niinimäki, and S. Saarakkala, "Acoustic emissions and kinetic instability as new clinical biomarkers to noninvasively assess knee osteoarthritis," *Osteoarthritis Cartilage*, vol. 26, no. 1, pp. S40–S41, Apr. 2018.

[40] B. Mascaro, J. Prior, L.-K. Shark, J. Selfe, P. Cole, and J. Goodacre, "Exploratory study of a non-invasive method based on acoustic emission for assessing the dynamic integrity of knee joints," *Med. Eng. Phys.*, vol. 31, no. 8, pp. 1013–1022, Oct. 2009.

[41] L.-K. Shark, "Discovering differences in acoustic emission between healthy and osteoarthritic knees using a four-phase model of sit-stand-sit movements," *Open Med. Informat. J.*, vol. 4, no. 1, pp. 116–125, Aug. 2010.

[42] L.-K. Shark, H. Chen, and J. Goodacre, "Knee acoustic emission: A potential biomarker for quantitative assessment of joint ageing and degeneration," *Med. Eng. Phys.*, vol. 33, no. 5, pp. 534–545, Jun. 2011.

[43] L.-K. Shark, H. Chen, W. Quan, and J. Goodacre, "Acoustic emission and angular movement variations from early adulthood healthy knees to late adulthood osteoarthritic knees," in *Proc. 38th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Orlando, FL, USA, Aug. 2016, pp. 2382–2385.

[44] T. I. Khan, M. Kusumoto, Y. Nakamura, S. Ide, and T. Yoshimura, "Acoustic emission technique as an adaptive biomarker in integrity analysis of knee joint," *J. Phys. Conf. Ser.*, vol. 1075, no. 1, Aug. 2018, Art. no. 012020.

[45] T. I. Khan *et al.*, "Acoustic emission measurement as adaptive biomarker in integrity analysis of knee osteoarthritis," *J. Multimodal User Interface*, vol. 10, pp. 319–324, Dec. 2016.

[46] D. Choi, S. Ahn, J. Ryu, M. Nagao, and Y. Kim, "Knee acoustic emission characteristics of the healthy and the patients with osteoarthritis using piezoelectric sensor," *Sensors Mater.*, vol. 30, no. 8, pp. 1629–1641, Aug. 2018.

[47] M. Browne, D. Barrett, A. Balabanis, and C. Rowland, "Passive monitoring of knee joint condition using acoustic emission," *Proc. Orthopaedic*, vol. 98-B, no. 1, p. 54, 2016.

[48] I. Vatolik, G. Hunter, M. Everington, and A. T. Augousti, “A multimodal sensor network to detect and monitor conditions consequential to knee injuries,” in *Proc. 12th Int. Conf. Intell. Environ. (IE)*, London, U.K., Sep. 2016, pp. 175–177.

[49] H. Schwalbe, “Detection of defects in the human skeletal system and production of failure optimized artificial bone applying acoustic emission analysis (AEA),” presented at the 31st Conf. Eur. Working Group Acoustic Emission, Sep. 2014. [Online]. Available: http://www.ewgae2014.com/portals/131/bb/fr3a1.pdf

[50] B. Semiz, S. Hersek, D. C. Whittingslow, L. A. Ponder, S. Prahalad, and O. T. Inan, “Using knee acoustical emissions for sensing joint health in patients with juvenile idiopathic arthritis: A pilot study,” *IEEE Sensors J.*, vol. 18, no. 22, pp. 9128–9136, Nov. 2018.

[51] B. Semiz, S. Hersek, D. C. Whittingslow, L. Ponder, S. Prahalad, and O. T. Inan, “Change point detection in knee acoustic emissions using the teager operator: A preliminary study in patients with juvenile idiopathic arthritis,” in *Proc. IEEE EMBS Int. Conf. Biomed. Health Inform. (BHI)*, Chicago, IL, USA, May 2019, pp. 1–4.

[52] S. Hersek *et al.*, “Acoustical emission analysis by unsupervised graph mining: A novel biomarker of knee health status,” *IEEE Trans. Biomed. Eng.*, vol. 65, no. 6, pp. 1291–1300, Jun. 2018.

[53] D. C. Whittingslow, H.-K. Jeong, V. G. Ganti, N. J. Kirkpatrick, G. F. Kogler, and O. T. Inan, “Acoustic emissions as a non-invasive biomarker of the structural health of the knee,” *Ann. Biomed. Eng.*, vol. 48, no. 1, pp. 225–235, Jan. 2020.

[54] D. Glaser, R. D. Komistek, H. E. Cates, and M. R. Mahfouz, “A non-invasive acoustic and vibration analysis technique for evaluation of hip joint conditions,” *J. Biomech.*, vol. 43, no. 3, pp. 426–432, Feb. 2010.

[55] F. Kummer and W. L. Jaffe, “Feasibility of using ultrasonic emission for clinical evaluation of prosthetic hips,” *Bull. NYU Hospital Joint Diseases*, vol. 68, no. 4, pp. 262–265, 2010.

[56] A. J. FitzPatrick, G. W. Rodgers, G. J. Hooper, and T. B. F. Woodfield, “Development and validation of an acoustic emission device to measure wear in total hip replacements *in-vitro* and *in-vivo*,” *Biomed. Signal Process. Control*, vol. 33, pp. 281–288, Mar. 2017.

[57] L. Roffe, A. J. FitzPatrick, G. W. Rodgers, T. B. F. Woodfield, and G. J. Hooper, “Squeaking in ceramic-on-ceramic hips: No evidence of contribution from the trunnion morse taper,” *J. Orthopaedic Res.*, vol. 35, no. 8, pp. 1793–1798, Aug. 2017.

[58] G. W. Rodgers, R. Welsh, L. J. King, A. J. FitzPatrick, T. B. F. Woodfield, and G. J. Hooper, “Signal processing and event detection of hip implant acoustic emissions,” *Control Eng. Pract.*, vol. 58, pp. 287–297, Jan. 2017.

[59] G. W. Rodgers *et al.*, “Acoustic emission monitoring of total hip arthroplasty implants,” *IFAC Proc. Volumes*, vol. 47, no. 3, pp. 4796–4800, Jan. 2014.

[60] J. Prior *et al.*, “Analysis of high frequency acoustic emission signals as a new approach for assessing knee osteoarthritis,” *Ann. Rheumatic Diseases*, vol. 69, no. 5, pp. 929–930, May 2010.

[61] R. Schwarzkopf, F. J. Kummer, and W. L. Jaffe, “Acoustic emission studies of posterior stabilized and cruciate retaining knee arthroplasties.,” *J. Knee Surg.*, vol. 24, no. 3, pp. 185–190, Sep. 2011.

[62] C. E. H. Scott, M. J. Eaton, R. W. Nutton, F. A. Wade, S. L. Evans, and P. Pankaj, “Metal-backed *versus* all-polyethylene unicompartmental knee arthroplasty: Proximal tibial strain in an experimentally validated finite element model,” *Bone Joint Res.*, vol. 6, no. 1, pp. 22–30, Jan. 2017.

[63] C. E. H. Scott, M. J. Eaton, R. W. Nutton, F. A. Wade, P. Pankaj, and S. L. Evans, “Proximal tibial strain in medial unicompartmental knee replacements: A biomechanical study of implant design,” *Bone Joint J.*, vol. 95, no. 10, pp. 1339–1347, Oct. 2013.

[64] G. Qi and J. Li, “Experimental–computational solution to fatigue induced microcrack source localization in cemented hip arthroplasty models,” *NDT E Int.*, vol. 40, no. 5, pp. 378–389, Jul. 2007.

[65] Y. Yamada, S. Wakayama, J. Ikeda, and I. Miyaji, “Long-term reliability assessment of ceramic femoral head based on microfracture analysis using acoustic emission technique,” in *Proc. IFMBE*, Singapore, 2010, pp. 608–611.

[66] J. Li and G. Qi, “Fatigue induced damage in cemented arthroplasty can be investigated by acoustic emission,” presented at the Amer. Soc. Biomech. Conf., Aug. 2007. [Online]. Available: http://www.asbweb.org/conferences/2007/211.pdf

[67] C. Rowland, M. Browne, A. Taylor, and U. K. Leatherhead, “Dynamic health monitoring of metal on metal hip prostheses using acoustic emission,” in *Proc. 26th Eur. Conf. Acoustic Emission Test.*, Berlin, Germany, 2004, pp. 465–467.

[68] G. Ouenzerfi, F. Massi, E. Renault, and Y. Berthier, “Squeaking friction phenomena in ceramic hip endoprosthesis: Modeling and experimental validation,” *Mech. Syst. Signal Process.*, vols. 58–59, pp. 87–100, Jun. 2015.

[69] N. E. D. Gueiral, E. M. da Silva Marques Nogueira, and A. M. de Amaral Monteiro Ramos, “Crack detection by wavelet-based acoustic emission test *in vitro* cemented implant,” *Mater. Sci. Forum*, vols. 638–642, pp. 558–563, Jan. 2010.

[70] F. J. Burgo, D. E. Mengelle, A. Ozols, C. Fernandez, and C. M. Autorino, “The damping effect of cement as a potential mitigation factor of squeaking in ceramic-on-ceramic total hip arthroplasty,” *Bone Joint Res.*, vol. 5, no. 11, pp. 531–537, Nov. 2016.

[71] P. Piriou, G. Ouenzerfi, H. Migaud, E. Renault, F. Massi, and M. Serrault, “A numerical model to reproduce squeaking of ceramic-on-ceramic total hip arthroplasty. Influence of design and material,” *Orthopaedics Traumatol., Surg. Res.*, vol. 102, no. 4, pp. 229–234, Jun. 2016.

[72] D. Glaser, R. D. Komistek, H. E. Cates, and M. R. Mahfouz, “Clicking and squeaking: *In vivo* correlation of sound and separation for different bearing surfaces,” *J. Bone Joint Surg. Amer. Volume*, vol. 90, no. 4, pp. 112–120, Nov. 2008.

[73] G.-H. Feng and W.-M. Tseng, “PZT and PNIPAM film-based flexible and stretchable electronics for knee health monitoring and enhanced drug delivery,” *IEEE Sensors J.*, vol. 18, no. 23, pp. 9736–9743, Dec. 2018.

[74] G.-H. Feng and W.-M. Chen, “Acoustic emission wave sensor with thermally controllable force-enhancement mechanism for acoustic emission source detection and biomedical application,” in *Proc. IEEE Electron Devices Technol. Manuf. Conf. (EDTM)*, Toyama, Japan, Feb. 2017, pp. 213–215.

[75] G.-H. Feng and W.-M. Chen, “Piezoelectric-film-based acoustic emission sensor array with thermoactuator for monitoring knee joint conditions,” *Sens. Actuators A, Phys.*, vol. 246, pp. 180–191, Aug. 2016.

[76] G.-H. Feng and W.-M. Chen, “Flexible acoustic emission sensor array with thermoresponsive actuator enhancing sensitivity for monitoring osteoarthritis,” in *Proc. Transducers 18th Int. Conf. Solid-State Sensors, Actuat. Microsyst. (TRANSDUCERS)*, Anchorage, AK, USA, Jun. 2015, pp. 678–681.

[77] L.-K. Shark, K. Huang, W. Quan, J. C. Waterton, M. A. Bowes, and J. Goodacre, “Acoustic emission sonification and magnetic resonance imaging-based kinematics for exploratory analysis of knee joints,” in *Proc. IEEE Int. Conf. Bioinf. Biomed. (BIBM)*, Shenzhen, China, Dec. 2016, pp. 1016–1022.

[78] G. Qi *et al.*, “3D real time methodology monitoring cement failures in THA,” *J. Biomed. Mater. Res.*, vol. 71A, no. 3, pp. 391–402, Dec. 2004.

[79] C. N. Teague, S. Hersek, J. L. Conant, S. M. Gilliland, and O. T. Inan, “Wearable knee health rehabilitation assessment using acoustical emissions,” in *Proc. AIP Conf.*, vol. 1806, 2017, Art. no. 070008.

[80] H. Toreyin, S. Hersek, C. N. Teague, and O. T. Inan, “A proof-of-concept system to analyze joint sounds in real time for knee health assessment in uncontrolled settings,” *IEEE Sensors J.*, vol. 16, no. 9, pp. 2892–2893, May 2016.

[81] R. P. Franke, P. Dorner, H. J. Schwalbe, and B. Ziegler, “Acoustic emission measurement system for the orthopedic diagnostics of the human femur and knee joint,” *J. Acoustic Emission*, vol. 22, pp. 236–242, Jan. 2004.

[82] C. N. Teague *et al.*, “A wearable, multimodal sensing system to monitor knee joint health,” *IEEE Sensors J.*, vol. 20, no. 18, pp. 10323–10334, Sep. 2020.

[83] C. N. Teague *et al.*, “Novel methods for sensing acoustical emissions from the knee for wearable joint health assessment,” *IEEE Trans. Biomed. Eng.*, vol. 63, no. 8, pp. 1581–1590, Aug. 2016.

[84] C. Teague *et al.*, “Novel approaches to measure acoustic emissions as biomarkers for joint health assessment,” in *Proc. IEEE 12th Int. Conf. Wearable Implant. Body Sensor Netw. (BSN)*, Cambridge, MA, USA , Jun. 2015, pp. 1–6.

[85] D. H. Kohn, “Acoustic emission and nondestructive evaluation of biomaterials and tissues,” *Crit. Rev. Biomed. Eng.*, vol. 23, nos. 3–4, pp. 221–306, 1995.

[86] A. I. Faisal, S. Majumder, T. Mondal, D. Cowan, S. Naseh, and M. J. Deen, “Monitoring methods of human body joints: State-of-the-art and research challenges,” *Sensors*, vol. 19, no. 11, p. 2629, Jun. 2019.

[87] R. L. Reuben, “Acoustic emission and ultrasound for monitoring the bone-implant interface,” in *Bone Response to Dental Implant Materials*, A. Piattelli, Ed. Cambridge, U.K.: Woodhead, 2017, ch. 13, pp. 247–259.

[88] J. H. Cachão *et al.*, "Altering the course of technologies to monitor loosening states of endoprosthetic implants," *Sensors*, vol. 20, no. 1, p. 104, Dec. 2019.

[89] A. R. Remya *et al.*, "Hip implant performance prediction by acoustic emission techniques: A review," *Med. Biol. Eng. Comput.*, vol. 58, no. 8, pp. 1637–1650, Jun. 2020.

[90] G. Qi, J. Li, W. P. Mouchon, and G. Lewis, "Defect-induced fatigue microcrack formation in cement mantle," *J. Biomed. Mater. Res. A*, vol. 75A, no. 2, pp. 414–424, Nov. 2005.

[91] N. Gueiral and E. Nogueir, "Acoustic emission studies in hip arthroplasty–peak stress impact *in vitro* cemented prosthesis," in *Recent Advances in Arthroplasty*, S. Fokter, Ed. London, U.K.: IntechOpen, 2012, pp. 132–146.

[92] K. Kulkarni *et al.*, "Obesity and osteoarthritis," *Maturitas*, vol. 89, pp. 22–28, Jul. 2016.

[93] Y. Yamada, S. Wakayama, J. Ikeda, and F. Miyaji, "Fracture analysis of ceramic femoral head in hip arthroplasty based on microdamage monitoring using acoustic emission," *J. Mater. Sci.*, vol. 46, no. 18, pp. 6131–6139, Sep. 2011.

[94] A. Khan-Edmundson *et al.*, "Tissue attenuation characteristics of acoustic emission signals for wear and degradation of total hip arthoplasty implants," *Proc. IFAC*, vol.45, no. 18, pp. 355–360, 2012.

Liudmila Khokhlova received the B.Sc. (Hons.) and M.Sc. (Hons.) degrees in biomedical engineering from Tomsk Polytechnic University, Tomsk, Russia, in 2011 and 2013, respectively. She is currently pursuing the Ph.D. degree with the Tyndall National Institute, Cork, Ireland.

Since 2014, she has been an Electronic Engineer with Tomsk State University, Tomsk, Russia. Her research interests include biomedical data analysis and interpretation, and wearable devices for health and well-being, in particular, for orthopedic applications and rehabilitation.

Dimitrios-Sokratis Komaris was born in Thessaloniki, Greece, in 1987. He received the M.Eng. degree in mechanical engineering from the Aristotle University of Thessaloniki, Greece, in 2013, and the M.S. and Ph.D. degrees in biomedical engineering from the University of Strathclyde, Glasgow, U.K., in 2014 and 2018, respectively.

Since 2018, he has been a Postdoctoral Researcher with University College Cork, Tyndall Institute of Technology, Cork, Ireland. His research interests include clinical gait analysis and biomechanical assessment, injury prevention, and wearables for sports performance and clinical applications.

Salvatore Tedesco (Member, IEEE) received the B.Sc. (Hons.) degree in information technology engineering and the M.Sc. (Hons.) degree in telecommunications engineering from the University of Salento, Lecce, Italy, in 2008 and 2011, respectively.

Since April 2012, he has been with the Wireless Sensor Networks Group, Tyndall National Institute, University College Cork (UCC), Cork, Ireland, where he is currently a Senior Researcher—Team Leader. He has authored more than 50 articles in international journals and conference proceedings. His research interests include wearable technologies for healthcare and well-being, human movement analysis in sports and clinical populations, motion sensors, signal processing, data analytics, and machine learning. Further contributions deal with RFID technology and antenna design, and ultrawideband localization systems for indoor applications.

Brendan O'Flynn (Senior Member, IEEE) received the B.Eng. (Hons.), M.Eng.Sc., and Ph.D. degrees from University College Cork, Ireland, in 1993 and 1995, respectively.

He is currently a Senior Staff Researcher with the Tyndall National Institute, Cork, Ireland. He is also the Head of the Wireless Sensor Networks (WSN) Group. His research interests include wearable sensing systems, edge-based analytics, sensor system integration, low power embedded systems design and development, system miniaturization, and RF system design and optimization. He has published widely in these areas and has secured significant funding for the development and deployment of "Smart Sensing" technologies and applied research projects.