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Chapter

Acoustic Monitoring of Joint Health

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Abstract

The joints of the human body, especially the knees, are continually exposed to varying loads as a person goes about their day. These loads may contribute to damage to tissues including cartilage and the development of degenerative medical conditions such as osteoarthritis (OA). The most commonly used method currently for classifying the severity of knee OA is the Kellgren and Lawrence system, whereby a grade (a KL score) from 0 to 4 is determined based on the radiographic evidence. However, radiography cannot directly depict cartilage damage, and there is low inter-observer precision with this method. As such, there has been a significant activity to find non-invasive and radiation-free methods to quantify OA, in order to facilitate the diagnosis and the appropriate course of medical action and to validate the development of therapies in a research or clinical setting. A number of different teams have noted that variation in knee joint sounds during different loading conditions may be indicative of structural changes within the knee potentially linked to OA. Here we will review the use of acoustic methods, such as acoustic Emission (AE) and vibroarthrography (VAG), developed for the monitoring of knee OA, with a focus on the issues surrounding data collection and analysis.

Keywords: ultrasound, acoustic emission, vibroarthrography, osteoarthritis, knee joint

1. Introduction

1.1 Synovial joints and osteoarthritis

The free moving joints within the body are known as synovial joints and have the primary purpose of allowing forces applied to the skeleton to be transmitted as smooth, low-friction movements. The joint capsule, working alongside the muscles, tendons and ligaments stabilises the joint, whilst articular (or hyaline) cartilage covering the end of the bones in combination with synovial fluid within the joint space provides the environment for smooth, well-lubricated movements [1, 2]. In addition, some joints also contain fibrocartilaginous discs between the two bones to support the other joint components and dissipate the forces experienced by the joint, for instance, intervertebral discs in the spine, or the meniscus within the knee.

Osteoarthritis affects all of the structures within the joint and is defined as a condition causing pain within the joint, loss of function and decreased quality of life for patients [3]. The disease results in the degradation of cartilage and subsequent sclerosis and lesions in the now exposed subchondral bone, along with inflammation in the joint [4]. Tears within cartilaginous structures and new

interactions between cartilage and bone, along with bone and bone, make for less smooth movements, pain, stiffness and reduction in joint function.

1.2 Epidemiology and impact

The most common joints affected by osteoarthritis include those of the knee, hip and hands with osteoarthritis of the knee the most commonly occurring form, affecting over 18% of the population in England [5].

With such a large proportion of the population affected, musculoskeletal conditions including osteoarthritis have considerable impact both medically and economically. Clinically, the pain and loss of function associated with osteoarthritis result in a lower quality of life reported by patients, who require a large number of GP visits and hospital admissions [6–8].

The underlying pathophysiology of osteoarthritis is unclear, with genetics, age, gender, obesity and previous injury all contributing to varying degrees in disease development and progression. The heterogeneous nature of the disease makes targeted treatment of cause and prevention of progression a challenge, with current best practice centring on patient education and lifestyle changes surrounding exercise, use of analgesics and anti-inflammatories to manage pain and inflammation and finally joint replacement at the severe end of the spectrum of disease [9]. However, this approach, with the exception of exercise targeting weight loss and strength, does not address an underlying cause or prevent progression of disease, an aspiration of future interventions for the disease.

Ranking the sixth most common cause of disability globally in 2010 [10], musculoskeletal conditions, including osteoarthritis, impact not only the healthcare system and patients but also their families [11]. Patients and their carers are at greater risk of being out of employment [12], with only 63% of those with a musculoskeletal condition in employment compared to 82% in those without a health condition [13].

With a predicted increase in the ageing population and an increase in obesity [14–16], the burden on health services and economic impact in terms of lost work time and disability is of growing concern. There is a real need for means of non-invasive early detection of osteoarthritis, sensitive means of monitoring progression and development of efficacious treatments to prevent and improve symptoms in order to improve quality of life and reduce the numbers progressing to severe disease and requiring joint replacement.

2. Standard methods of detection

Osteoarthritis is a condition affecting a multitude of tissues within a joint, and as such, approaches which give information to the clinician on bone, muscle, cartilaginous tissue and the microenvironment within a joint are required to give a full picture of the condition of a joint. Imaging is currently the main diagnostic tool used to assess osteoarthritis. Dependent upon the form of imaging used, a variety of tissues can be examined as markers of disease state and progression.

In clinical practice, a combination of clinical presentation and X-radiography (X-ray) is used to diagnose osteoarthritis. When a patient presents as over 45 years of age, with typical symptoms of osteoarthritis including pain within the joint during activity and minimal stiffness within the joint in the morning lasting no more than 30 min, then X-ray is not indicated for diagnosis [9, 17].

However, X-ray is useful when differential diagnosis is possible, and in certain scenarios, magnetic resonance imaging is used to give additional information on damage to tissues within the joint and inform treatment options.

2.1 X-radiography

X-ray works upon the principle of differential absorbance of radiation by different tissues, with dense tissues such as the bone absorbing a large proportion of the radiation compared to soft tissues such as the muscle and connective tissue.

As a result, the bone appears bright white on images and can be studied for changes in morphology, whereas soft tissues show less differentiation and are not easily examined.

The current gold standard in the diagnosis of osteoarthritis from radiographic images involves the scoring of X-ray images using the Kellgren-Lawrence (KL) scale. The Kellgren-Lawrence is a five-point scale which categorises disease severity based upon the assessment of bony changes, appearances of osteophytes and joint space narrowing within the joint [18]. The description of the radiographic findings at different KL grades can be seen in **Table 1**.

The KL scale was first described in 1957 in response to an identified need to standardise the definition of changes within an osteoarthritic joint in order to improve inter-rater reliability when reporting the disease [18]. Thorough analysis of the performance of the scale at joints throughout the body revealed that whilst correlation between the defined changes and osteoarthritis were observed at all joints bars the wrist, the greatest inter-rater agreement was found within the knee joint. Intra-rater repeatability followed a similar trend with slightly better agreement between readings. This has subsequently been reflected in the most common use of the scale in the assessment of the knee joint.

More recent comparison of radiographic scoring systems has established that for the knee joint, the KL scale has stood the test of time, with no subsequently developed grading systems outperforming the inter-rater repeatability of this scale [19]. However, whilst the limit of inter and intra-observer reliability in assessing radiographic osteoarthritis may have been reached (correlation coefficients around 0.8), it is acknowledged that a more diverse manner of assessment of osteoarthritis may be warranted to improve sensitivity when assessing disease progression and specificity for aspects of the homogeneous pathophysiology underlying the disease.

In terms of sensitivity, KL scoring of radiographs does not perform well in the detection of early disease or in the monitoring of disease progression, where large time periods are required to observe a change in category during which time symptomatic progression may have occurred [20].

Alone, radiographic assessment using the Kellgren-Lawrence scale allows direct assessment of bony changes such as osteophyte formation, however, relies on indirect measures of joint space narrowing to assess cartilaginous change. The surrogate marker of joint space narrowing in place of direct measurement of cartilage, whilst

Grade	Description of radiographic findings
0	No evidence of radiographic osteoarthritis
1	Doubtful narrowing of the joint space and possible osteophytic lipping
2	Definite osteophytes and possible narrowing of the joint space
3	Moderate multiple osteophytes, definite narrowing of the joint space, small pseudocystic areas with sclerotic walls and possible deformity of bone contour
4	Large osteophytes, marked narrowing of joint space, sever sclerosis and definite deformity of bone contour

Table 1.
Kellgren-Lawrence scale description of radiographic findings.

important in the sensitivity of Kellgren-Lawrence scale to disease severity, does not perform well when compared with changes observed arthroscopically [19, 21].

This may go some way to explaining the disparity in patient symptom reporting in the form of self-reported osteoarthritis, clinically diagnosed osteoarthritis and disease severity suggested using the Kellgren-Lawrence scale [22]. In addition to indirect cartilage measurements, the Kellgren-Lawrence score is based solely on the femorotibial joint. As osteoarthritis can also affect the patellofemoral joint, this could account for further disparity between symptoms and radiographic severity of disease [20].

2.2 Magnetic resonance imaging

In contrast to X-radiography, magnetic resonance imaging (MRI) can directly image a number of tissues, including the cartilage, bone and fluids such as that found in the synovium. Several approaches have been taken to the assessment of joints with suspected osteoarthritis using MRI.

A number of joint-specific semi-quantitative scoring systems have been developed using features considered important in osteoarthritis disease manifestation, including bone marrow lesions, meniscal scores and scores of cartilage loss. For the knee, the scoring systems developed include the whole-organ MRI score (WORMS), the knee osteoarthritis scoring system (KOSS), the Boston-Leeds OA knee scoring (BLOKS) and the MRI osteoarthritis knee score (MOAKS), which brings together the strengths of the WORMS and BLOKS systems whilst standardising the definitions used [23].

Quantitative analysis of specific tissues has also been used to measure thickness, area and volume of cartilage, bone area and area of the bone that is denuded, as well as combining the two to assess cartilage thickness over areas of denuded bone. Whilst concentrating on a smaller region of the joint, this approach removes some of the subjectivity associated with the semi-quantitative scores detailed above, both for MRI and X-ray scoring [23–26].

The benefits of MRI for use both clinically and within research are a trade-off between increased sensitivity and specificity and protocols which are realistic for application in a given setting. Semi-quantitative MRI protocols can be performed using clinical MRI equipment, however, have the same caveats of KL scoring of X-rays in terms of inter and intra-rater reliability.

Quantitative measures of the cartilage and bone remove some of the subjective elements of semi-quantitative assessment. The changes of cartilage and bone measurements can be exceedingly small in magnitude, allowing assessment of much smaller anatomical change over shorter timeframes than those observed using X-ray. Making such small measurements presents its own challenges and is time-consuming, whilst producing such small measurements of change that relationship to clinical outcomes can be weak [27]. However, being direct in nature, quantitative measures have shown promise in improving association of imaging techniques with disease symptoms and progression compared with KL scoring of X-rays. Denuded bone area has been shown to correlate with concurrent and incident knee pain [28], whilst changes in cartilage thickness have been linked to the likelihood of disease progression to the point of needing knee joint replacement surgery [29, 30].

In addition to semi-quantitative and quantitative measurements, the use of contrast and powerful MRI imaging protocols extend the means to assess tissue, enabling assessment of components of the ultrastructure of articular cartilage and the meniscus along with the synovial fluid via compositional and diffusion MRI, respectively. This makes MRI a potentially powerful tool in assessing the impact of osteoarthritis on the entirety of a joint, as well as in identifying factors driving disease and predicting disease progression.

High-resolution MRI protocols and high doses of contrast prove most useful in research aimed at understanding of the mechanisms of osteoarthritis and assessment of disease progression or slowing with intervention. However, these are time-consuming protocols and contrast doses can far outstrip recommended doses accepted in clinical practice [31].

The added power of MRI in the assessment of osteoarthritis is most likely to remain predominantly within the research field at this point in time, as access to advanced equipment, lack of uniform protocols and the time-consuming nature of post-processing that is required limits use clinically.

2.3 Other biomarkers of osteoarthritis

Whilst X-Ray and MRI are the two primary forms of imaging used to assess osteoarthritic joints, both computer tomography (CT) and ultrasound have also been employed for this purpose, generally in a research setting, where MRI is proving to provide greatest accuracy [32]. For CT, the use is limited due to CT scans delivering a high radiation dose without delivering significantly greater sensitivity to disease progression than X-ray or MRI.

Whilst ultrasound allows direct imaging of the cartilage which is not obtained during X-ray, interpretation and observations made can vary between operators, especially at joints further from the surface of the skin. This is least marked in superficial joints, and assessment of inflammation and effusion has drawn parallels with disease severity and progression [33–35]. Therefore, ultrasound may be most useful in adding measures associated with inflammation when assessing joints of the hand rather than the knee and hip which are much deeper joints.

Finally, biochemical markers associated with inflammation and degradation of the bone and cartilage are under investigation as additional biomarkers for osteoarthritis. This presents its own challenges as whilst these markers may well be sensitive to change in internal environment, their specificity to osteoarthritis and location of degeneration are proving more of obstacle, with generally weak associations seen between biochemical biomarkers of disease and measures of use in assessing disease severity and progression [36, 37]. That said, there is some evidence that markers may be able to offer additional strength in assessing osteoarthritis severity and response to treatments with further research [38].

2.4 Current challenges in diagnosis and treatment

Individually the current means to diagnose and assess progression of osteoarthritis are limited by one or more factors, namely, subjectivity of measures including high inter- and intra-rater repeatability in semi-quantitative imaging, low sensitivity for change in disease state or low specificity for disease tissue or location.

This presents challenges when making informed clinical decisions, investigating new interventions and determining the effects of preventative measures on disease progression. The low sensitivity of current biomarkers also limits the application of stratified medicine in the approach to new treatments, an area that is of particular interest given the marked clinical and biological heterogeneity of this condition [39].

As the disease is driven by multiple pathogenic factors, it may be that a combination of multiple diagnostic measures is required to develop a sensitive biomarker for osteoarthritis. This concept is currently demonstrated through the development of computational risk factor tools based on a range of self-reported osteoarthritis risk factors, aimed at patient education and pre-emptive lifestyle intervention [40–42]. More recently, the tool for osteoarthritis risk prediction has proven inclusion of MRI measures in combination with KL scored radiographs provides a more powerful predictive

tool for predicting disease progression [43]. Furthering this approach using other potential biomarkers for osteoarthritis, including imaging and biochemical markers of cartilage and bone change, may allow even greater sensitivity and specificity.

With this in mind, research has progressed in innovative approaches to develop biosensors that address aspects of osteoarthritis that are currently unmeasured. To date, all biomarkers for the disease consider circulating biochemicals or images of the knee in a static state. As the symptoms of osteoarthritis relate directly to movements of the joint, a novel approach to assessing changes in interactions between tissues during joint movement is being investigated using acoustics within the joint.

3. Acoustic medical technologies for joint health

Due to its non-invasive nature, the use of sound or vibration has found many medical applications associated with the musculoskeletal system.

For instance, as discussed above, ultrasound imaging, or ultrasonography (US), can be a useful tool in rheumatology. It is increasingly used to image and evaluate the inflammatory aspects of rheumatic diseases as an assessment tool for tendons and soft tissue [44, 45]. It has been applied to osteoarthritis specifically, having been shown to be a sensitive tool for the evaluation of synovitis (joint inflammation) and joint effusion (the flow of blood and other fluids in joints), through direct imaging and the use of Doppler signal analysis, a form of flow velocimetry [44–48]. Whilst US can be used for imaging musculoskeletal changes in osteoarthritis, such as changes in cartilage thickness, it is limited. It has been noted that US may be limited in assessing cartilage in larger weight-bearing joints [49] because of the inherent inability of ultrasound to pass through denser bony structures and therefore penetrate to the deeper portions of the joint [50]. The central portion of thick joints cannot be visualised with US [51], but US can detect osteophytosis (bone spurs forming around joints) at greater rates than conventional radiography. Being non-ionising and able to image soft tissues, US is a good alternative to radiographic imaging. Magnetic resonance imaging (MRI) offers excellent tissue contrast and anatomical resolution compared to US [49]. MRI can detect changes in the volumes of cartilage, whereas US is only capable of quantifying changes in thicknesses. Therefore, whilst MRI is more expensive, US is primarily only used as an alternative for anatomical imaging when there is hardware present within the patient, i.e. implants and some older cardiac defibrillators and pacemakers, which precludes the use of MRI [52].

As well as for imaging, ultrasound can be utilised directly as a treatment for OA [53, 54]. The management of OA involves the relief of pain and the maintenance or improvement of joint function. The American College of Rheumatology (ACR) and the European League Against Rheumatism (EULAR) recommend a combination of pharmacological and nonpharmacological treatments [55]. Various nonpharmacological treatments, including exercise, physical therapy, hot packs and therapeutic ultrasound (TU) etc., exist with varying evidence of efficacy. In TU, mechanical energy in the form of pulsed or continuous high-frequency vibrations is applied directly to the joint [56]. This is reputed to reduce oedema or cysts [57], as well as reduce inflammation, relieve pain and accelerate tissue repair; however, results of clinical studies are conflicting [55, 56]. The applied ultrasonic vibrations cause atomic oscillations in the tissue; the amplitude of which depends on the intensity or power of the applied beam. When applied continuously, this can result in thermal effects in the tissue, which are reduced when the beam is pulsed [56]. When the ultrasonic beam has high intensity, the atoms in the attenuating medium no longer oscillate around their equilibrium position but have a net motion along the axis of the beam [53]. This can result in damage or micro-machining due to the

ultrasound-induced forces, allowing TU to be used as a surgical tool [53]. High-intensity TU can also result in the movement of particles and fluid within the tissue. This phenomenon has been used to drive pharmaceuticals, such as non-steroidal anti-inflammatory drugs (NSAIDs) and corticosteroids, into the tissue [58, 59], facilitating local delivery.

3.1 Acoustic detection

Spontaneous emission of acoustic waves and other vibrations has been recorded during the flexion and extension of joints, as well as the fracture and wear of bones and implants [60, 61]. Studies have shown that these vibrations are affected by musculoskeletal disorders in joints, making vibration monitoring a useful diagnostic tool [62]. However, joints are highly complex heterogeneous structures over a wide range of length scales. Parameters like wave velocity, dispersion and attenuation all affect how waves travel through tissues, making interpretation of the waveform complicated. The following techniques have been developed to resolve this issue:

3.1.1 Phonoarthrography

The earliest studies on the monitoring of the spontaneous emission of acoustic waves were based on the use of stethoscopes to amplify audible sounds generated within joints [63, 64]. Early joint auscultation in this manner was initially a manual process and was inherently subjective. Still, these studies showed that whilst there are 'normal joint sounds', the sound produced is affected by different kinds of injury and arthritis [65]. That said, this method is not yet used in primary care and has only received modest attention in the literature since its first appearance in 1902 [63, 66].

Later studies attempted to reduce the subjectivity of this method by recording the sounds using microphones in conjunction with joint measurement technologies such as goniometers and video tracking [67]. Several of these studies note that pathological signals have major frequency components at low frequencies, that is, below 1000 Hz [64, 68]. The sensitivity range of the microphones used is usually in the range 50 Hz to 15 kHz; however, it has been suggested that standard acoustic recording microphones are not appropriate for the monitoring of joint signals, being too sensitive to background noise, with vibration transducers, or contact sensors, and accelerometers being preferred [61, 69]. Studies such as that by Chu et al. employed a differential microphone pair for noise cancellation and bandpass filters to minimise low-frequency movement artefacts and high-frequency transducer noise to mitigate this issue [61]. Conversely, other studies [70] suggest that as microphones are able to detect higher frequencies and no direct contact with the body is required, the combination of signals from both microphones and accelerometers might perform better than anyone signal alone.

Data analysis in early studies generally only used traditional stationary spectrum estimation methods using oscilloscopes or narrow-band spectrum analysers, with key measures being the frequency, wavelength, wave number and amplitude [64]. However, it is clear that the signals are nonstationary in nature, especially as different signals are generated at different joint positions [69]. As a result of this observation, more sophisticated spectral analysis methods were developed. One method is short-time Fourier analysis on segmented data where it is assumed that the data is stationary within each segment. This allows trends in the frequency component of the signal to be correlated with joint angle. The determination of the segments introduces subjectivity into the analysis. Therefore, techniques to track the nonstationarities in the signal, such as adaptive segmentation, linear prediction and autoregressive moving averages (ARMA), have been incorporated into the analysis [69].

3.1.2 Vibroarthrography (VAG)

Whilst phonoarthrography is based on the sound produced during the flexion or extension of joints, in VAG all vibrations produced during movement are considered [62]. Consequently, it is more common for a single accelerometer to be used as the sensor rather than a microphone [71]. It is also very common for signals in a frequency range below 1000 Hz to be of primary focus [72], with sampling rates of the order 1–4 kHz. A key advantage of the low sampling rate is that it allows for wireless data acquisition and processing using simple microcontrollers or single-board computers [73, 74]. That said, it has been suggested [71, 75] that single signal processing may be limited and multi-channel recordings may lead to better discrimination of the severity and location of joint injury or disorder. In many cases noise mitigation is achieved through prefiltering (commonly using a bandpass filter from 10 Hz to 1 kHz) and amplification prior to digitization at a specified sampling rate [76, 77]. The digital signal may go through additional filtering, such as that conducted by Andersen et al. [78] who used a Kaiser-windowed finite impulse response (FIR) bandpass filter.

There are other rationales for using multiple sensors during VAG as it has been observed that VAG may pick up vibrations not necessarily just due to the joint directly or to external interference [79]. For instance, the 10 Hz signal generated by the rectus femoris muscle which activates during the extension of the leg could interfere with the VAG signal recorded from the skin surface over the patella [80]. As this signal may vary in a similar fashion to the VAG signal, simple bandpass filtering may not be sufficient. It may be necessary to record the vibromyogram at the rectus femoris at the same time as the VAG signal and use adaptive filtering and noise cancellation techniques to isolate the VAG signal [79].

Therefore, the VAG signal is inherently nonstationary and potentially multicomponent in nature. The nature of the VAG signal means that it is not easily analysed using common signal processing techniques. This coupled with the difficulty in ascertaining the biological origin of the source of the signal is the main barrier to its use as a common diagnostic tool. As a result, much of the recent research activity has been focussed on feature extraction and statistical pattern classification [60]. Adaptive segmentation using least-square, linear prediction and autoregression algorithms is common [81, 82]. A host of statistical measures has been considered to characterise the VAG signal, including the form factors, skewness, kurtosis and entropy [71, 76]. It has also been shown that time-frequency distribution (TFD) [81, 83] and wavelet decomposition [84] are potentially powerful techniques for analysis and may negate the need for segmentation [83] but may be susceptible to noise [85]. These advancements have mostly been driven by developments in digital signal processing technologies that sped up analysis time as well as nonstationary signal analysis techniques developed for other biological signals like EEGs [84].

Using these techniques, spectral features such as frequency, energy and their respective spreads can be classified and linked to joint position, loading and pathology. The commonly used classifiers are neural network-based classifiers and support vector machines (SVM), as well as logistic regression and rule-based techniques [62, 71]. These neural networks and SVMs are supervised learning algorithms which search for a number of independent training data patterns taken from signals measured from participants with known pathologies to characterise new signals. These classification algorithms are increasingly dependable and can perform well with a limited amount of data. A number of different variants of these algorithms and classifiers have been investigated [60, 62]. Wu et al. [73] used an SVM based on the entropy and envelope amplitude features and achieved an overall accuracy of 83.56%. Nalband et al. [86] utilised an a priori algorithm with

a least-square SVM classifier and claim accuracy of 94.31% with a false discovery rate of 0.0892. Kręcisz [87] achieved accuracies of >90% using a logistic regression-based method. In each of these cases, the VAG signals were collected during knee flexion/extension motion using an accelerometer secured to the participants patella.

3.1.3 Acoustic emission (AE)

AE for biomedical applications is derived from non-destructive techniques developed for detecting damage in engineering materials, such as metals and composites [88]. AE occurs when materials locally under stress emit energy in the form of transient elastic waves. This allows for the monitoring of microcrack initiation and propagation in the bones and joints [89]—essential parts of bone remodelling [90], and wear [91, 92]. Other characteristic sounds in joints, such as the bursting of gas bubbles in synovial joints during movement, can also be detected using AE [93]. AE frequencies are usually in the ultrasonic range and so detection often involves the use of ultrasonic sensors.

A number of researchers have proposed AE sensor-based joint monitoring systems using piezoelectric films, electret or MEMS-based microphones.

Toreyin et al. [94, 95] used an off-the-shelf low-noise MEMS microphone in conjunction with gyroscope and accelerometer pairs in order to monitor sounds generated during various complex motions. The microphone used had a sensitivity range of 100 Hz to 10 kHz, and the researchers suggested that the MEMS-based microphone had a similar performance to an electret microphone [94]. The acoustic data were sampled at 100 kHz, and the inertial data (monitoring joint angle and limb movement) at 1 kHz, with the data being collected by a field programmable gate array (FPGA)-based real-time processor. It was noted that air microphones do not exhibit signal losses due to motion artefacts, but they are sensitive to ambient noise.

Teague et al. [96] compared a piezoelectric film-based contact microphone to two air microphones: one electret and one MEMS-based. The air microphones were used with a 15 Hz high-pass filter and a second-order low-pass filter with a cut-off frequency of 21 kHz and sampled at 44.1 kHz using an acoustic recorder. The piezoelectric microphone was used with a 100 Hz high-pass filter followed by a fourth order low-pass filter with a 10 kHz cut-off frequency. It was sampled at 50 kHz using custom circuits. The 100 Hz high-pass filter was chosen to attenuate the motion artefact noise. It was noted that the electret and MEMS microphones performed similarly in detecting joint sounds, although the electret sensor was significantly more expensive. They were both sensitive to ambient and interface noise, including rubbing of the tape securing the sensors. It was noted that the air microphones did not need to be in contact with the skin. Experiments with sensors positioned 5 cm off the skin captured similar acoustic signals, albeit with lower amplitude. The piezoelectric sensor was more sensitive to interface noise but less sensitive to background noise. Importantly, the contact microphone did not pick up higher frequency vibrations as distinctly as the air microphones which provided higher quality recordings as indicated by higher SNIRs.

Jeong et al. [97] used a low-noise electret microphone with a frequency range of 50 Hz to 20 kHz recorded by an audio recorder at a rate of 44.1 kHz. Signals were digitally filtered using a finite impulse response bandpass filter with a bandwidth from 1 to 15 kHz to prioritise short duration joint sounds whilst supressing interface noise.

Feng and Chen [98] developed a piezoelectric sensor comprised of a lead zirconium titanate (PZT) film deposited on titanium cantilever arrays as an acoustic sensing layer. This sensor uses a 1-mm-tall SU8 cylindrical probe on each cantilever to be in direct contact with the skin of the participant and transmit vibrations to the sensor. A thermoresponsive poly(N-isopropylacrylamide) (PNIPA) film was

integrated into the sensor to apply a force to the cantilever and hence improve contact between the probe and the skin when a current is applied across it. The sensor achieved a frequency range of up to 100 kHz, with at least one strong resonant peak at 390 Hz. A sampling rate of 2 MHz was used with a 1 kHz high-pass digital filter to remove low-frequency noise signals. Testing of the sensor on a butchered porcine leg during repeated joint flexure cycles revealed the presence of well-defined peaks located between 30 and 40 kHz, 60 and 70 kHz and 70 and 80 kHz. Similar trends to that observed with commercial AE sensors (the same used in the studies by Mascaro et al. in the JAAS system described later [99]) were noted during overuse of the joint.

Choi et al. [93] developed the bone joint acoustic sensor (BJAS). This has a pin-type probe on a disk-shaped piezoceramic supported by a damped metal plate. The structure is in a metal case with the probe in direct contact with the skin. The system used in conjunction with IMUs seems to have a frequency range of 100 Hz to 25 kHz and is sampled at 50 kHz.

Shark and Goodacre developed the joint acoustic analysis system (JAAS) [99, 100]. This system uses commercial piezoelectric contact ultrasonic acoustic sensors (with high sensitivity in the range 50–200 kHz but monitored over 20–400 kHz at a 1–5 MSPS sampling rate) [100] and electro-goniometers to provide joint angle-based AE during knee joint movement (see **Figure 1**). These commercial AE sensors use relatively thick piezoelectric bulk blocks for AE sensing and are housed in metal shells. The housing is fixed to the skin with surgical tape to maintain a rigid contact. The AE data acquisition operates in a non-continuous recording mode to minimise data volume. When the AE PCI data acquisition board is triggered by a signal value above a pre-set threshold, a 'hit' is recorded corresponding to an acoustic event. Each AE hit is recorded with a set of characteristic waveform features (i.e. dominant frequency, maximum amplitude and duration), and in addition the full waveforms were also stored, digitalized at a 1 MHz sampling frequency over a maximum duration of 15 ms [99]. The number of hits during each joint motion was used to determine a correlation with OA severity defined by KL scores determined using MRI data. It was noted that the frequency response of the acoustic sensor data is characterised by two peaks with a high probability of occurrence during

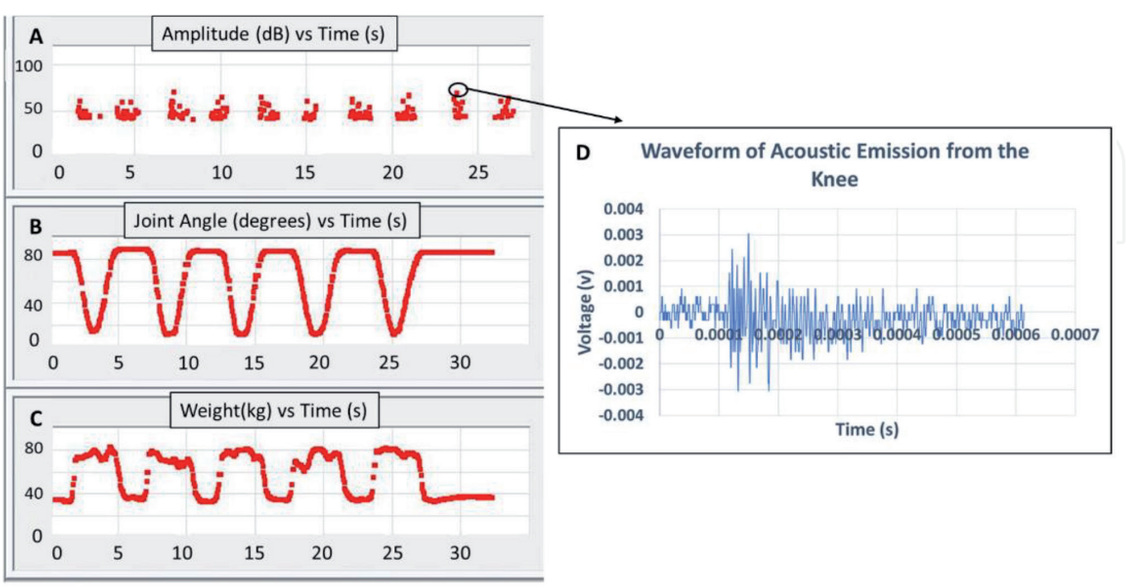

Figure 1.
Output from the joint acoustic analysis system (JAAS). Recording is made as the participant performs five sit-stand-sit movements. A: Acoustic 'hits' from a single knee recorded using a piezoelectric contact ultrasonic acoustic sensors. Each square indicates one acoustic emission captured by the system. For each 'hit' a waveform is also captured [D] from which waveform characteristics are calculated by the software. Alongside the acoustic emissions, joint angle [B] and weight through the leg [C] are also recorded.

knee measurements using a sit-stand-sit protocol, one in the low-frequency range (20–50 kHz) and the other one around 150 kHz. The latter frequency is mainly due to a peak of sensitivity of the sensor used [99].

4. Conclusion

Using radiographic techniques to monitor variations in joint structure and morphology is the classic method of quantifying OA. However, this technique is ionising, often requires multiple measurements as only the plane perpendicular to the radiation is observed and cannot monitor soft tissue directly. MRI can measure the thickness and volume of cartilage, but there are limitations with respect to time and cost. Ultrasound can monitor joint effusion and the thickness of cartilage, but it is not possible for ultrasound to penetrate thick bone tissue and observe the whole joint. There is the additional issue of subjectivity and the large difference in reproducibility based on the skill of those analysing the image. The use of invasive cameras in arthroscopy and joint endoscopy necessitate recovery after diagnosis. These techniques also do not facilitate measurements using dynamic movements. The use of acoustic sensors has the potential to quantify and classify joint pathology whilst removing the subjectivity of classic imaging techniques. Despite progress in detecting differences between type and severity of joint disorders, questions remain about the true origin and form of acoustic signals generated by joint structural changes. Thus, a significant part of the challenge linked to acoustic signal analysis resides in the retrieval of pertinent parameters from irrelevant information in a robust and statistically significant way [78].

As yet, whilst several protocols, sensor types and data analysis techniques have been developed, to date there is no consensus on the most adequate way to record and process vibration data [60]. The methodological aspects of acoustic assessments, such as sensor placement and outcomes measures have not been thoroughly investigated allowing doubt in the technique to remain. For instance, for knee investigations, many studies [73, 81, 101] favour what may be called an open kinematic chain configuration [102] whereby participants sit in a chair and lift their legs in a repetitive fashion, perhaps with weights attached. This has the advantage of being able to vary the load on the joint and allow for the inclusion of participants with advanced degenerative conditions or injuries affecting the limitation of the range of motion in the joint. A common alternative protocol involves repeated sit-stand-sit movements [103–105], creating a closed kinematic chain. This latter configuration perhaps has the advantage of forming a more natural loading of the knee joint. It potentially has the consequence of being inconsistent over time, as people can have the tendency of adjusting their movement to compensate for restricted or painful movement, thus changing the distribution of forces and moments acting on the knee [106]. Data comparing the protocols is limited, and there is no strong evidence for favouring one protocol over the other or indeed over alternatives, such as squatting [94, 102]. Given the protocol affects the loading of the joint and the frequency response of the vibration data generated, it also affects the potential consistency of the statistics derived therefrom and their subsequent interpretation for diagnostic and prognostic purposes. This suggests the necessity of a standard protocol if such techniques are to be used for monitoring the development of OA in an individual over time for clinical or research purposes.

Similarly, it is unclear what sort of vibrations and which frequency range is the most pertinent range to measure. In phonoarthrography acoustic waves in the audible range are of most interest. In VAG, focus is on low-frequency (<1000 Hz) vibrations, the cause and nature of which is more general. In AE, acoustic signals are of primary focus, albeit generally of a higher frequency than that used

in phonoarthrography. Whilst there is a significant amount of overlap between the techniques, there are important data that can be missed if one technique is favoured. There is little evidence to suggest that one technique is inherently better than the other, simply due to the lack of comparative studies. The lack of commonality in technique makes meta-analysis difficult. One limitation that is preventing the direct comparison is the lack of technologies that allow high-quality acoustic data to be collected at high sampling rates (>5 MSPS) for significant time periods as such sensors will inherently generate vast amounts of data requiring significant processing. Multiple sensors covering the different frequency ranges of interest are likely to be the way forward, but this strategy will have the disadvantage of comparing signals recorded at different sites, making the analysis more difficult. In any case, further study relating the acoustic signal back to the biomechanics of joint pathology may provide a stronger scientific basis to the causation of the signal, instead of relying on correlations. This will reduce the subjectivity of the analysis and facilitate diagnosis and prognosis, allowing this technique to become a powerful clinical tool.

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Conflict of interest

The authors declare that they have no conflict of interest.

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