Analysis of differences in vibroacoustic signals between healthy and osteoarthritic knees using EMD algorithm and statistical analysis

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Abstract. The knee joint is the largest and one of the most vulnerable and most frequently damaged joints in the human body. It is characterized by a complex structure. All articular surfaces are covered with hyaline cartilage. This cartilage has minimal regenerative capacity. Under the influence of cyclical micro-injuries, inflammatory mediators, prolonged excessive pressure or immobility, and thus disturbance of tissue nutrition, the cartilage becomes susceptible to damage and is easily covered with villi, cracks and abrasion. As a result, this translates into changes in the friction and lubrication processes within the joint and may affect the generated vibroacoustic processes. In this study, the signals recorded in a group of 28 volunteers were analysed, 15 of them were healthy people (HC) and 13 were people diagnosed with osteoarthritis (OA) qualified for surgery. The study aims to check the usefulness of the EMD (Empirical Mode Decomposition) algorithm in the filtration procedures of vibroacoustic signals. This algorithm is most often used in the analysis of signals that are most often nonlinear and non-stationary. Selected statistical indicators, such as RMS, VMS, variance and energy, were determined for the signals constituting the sum of the IMFs (Intrinsic Mode Functions) 1–8, having a normal distribution in the assessment of damage to the articular cartilage of the knee joint. Statistical analysis was performed for the values of individual indicators obtained. The vibroacoustic signals were recorded using CM-01B contact microphones placed in the central part of the medial and lateral joint fissure for movement in the range of 90°–0°–90° in closed kinetic chains (CKC) in the control group (HC) and the group of patients diagnosed with osteoarthritis (OA).

1. Introduction
The knee joint is one of the largest and at the same time one of the most sensitive and most frequently damaged joints in the human body. All joint surfaces in contact with each other are covered with articular cartilage, which is characterised by a very poor ability to regenerate [1–5]. Damage to articular cartilage is progressive, which is also influenced by co-occurring intra-articular damage such as meniscus and ligament damage or the influence of inflammatory mediators [1,6,7]. Given the progressive degradation...
of articular cartilage in the absence of adequate treatment and the irreversibility of changes that have already occurred, it seems extremely important to carry out rapid and accurate orthopaedic diagnostics.

The basis of any orthopaedic examination is taking a thorough history, performing a clinical examination including dedicated clinical tests different for each joint and the joint structure involved.

Articular cartilage is a structure that is not visible on a conventional X-ray. Therefore, imaging techniques such as an MRI are used to visualise the articular cartilage [8]. However, MRI is very costly, time-consuming and has limited availability. Furthermore, with the increasing popularity of MRI, it is becoming the first-line investigation in the diagnosis of the knee joint, often even bypassing a thorough clinical examination [9]. Such an approach results in long queues for those requiring diagnosis and may adversely affect the diagnostic effectiveness of the test results obtained. Moreover, MRI is of limited effectiveness in the diagnosis of cartilage lesions [10–12] and in most cases does not allow a correct estimation of the extent and degree of cartilage damage in the knee joints. Furthermore, MRI is less sensitive than clinical examination for ligamentous damage [13]. Early detection of knee joint pathology may help physicians to apply appropriate therapeutic procedures or refer the patient for surgical treatment [14,15]. Given the above, it seems important to introduce a form of screening to identify patients requiring more extensive tests. Such a method should be fast, low-cost and easy to perform. As articular cartilage degrades, it becomes cracked, uneven and the joint fluid changes its physiological properties [16], causing changes in the friction between the articular surfaces and therefore affecting the acoustic signals generated by the knee joint. The change in mechanical properties, in particular, the appearance of bumps, cracks or cartilage defects in the successive stages of degenerative changes [17,18] changes the vibroacoustic image during movement of the knee joint. Based on the generated vibroacoustic processes it is possible to assess the dynamic state of technical objects [19–21]. During knee movement, sound and vibration are generated by both intra-articular and extra-articular elements moving each other. [14,22,23]. Vibroarthrography is a diagnostic method to assess changes in the acoustic signals generated by the knee joint during movement [24,25]. As presented by Toreyin [26] the acoustic characteristics of the joint are constant for a given patient, independent of the activity performed before the test. This is important for the widespread use of vibroacoustic assessment since it can be carried out at any time of day, without special preparation of the patient for the examination. It is a completely non-invasive method, producing no ionizing radiation and easy to carry out even on the spot in the doctor’s office. Although the method of evaluating acoustic signals is relatively young, it is characterised by satisfactory sensitivity and specificity in the detection of intra-articular lesions [27].

However, despite the promising results of preliminary studies, so far no standardised testing protocol, sensors used, method of signal analysis or optimal placement of sensors on the examined joint has been developed [24]. The aim of this work was to test the diagnostic effectiveness of acoustic signal analysis in the assessment of cartilage damage to the knee joint using the EMD algorithm to analyse the collected material.

2. Materials and methods

2.1. Participants
The study was conducted on patients previously qualified for surgical treatment due to degenerative changes of the knee joint. Surgical qualification was conducted by an orthopaedic Participants specialist based on history, clinical examination and imaging studies. The day before the scheduled surgery, a vibroacoustic assessment was conducted in a hospital ward setting in accordance with a predetermined study protocol. Fifteen patients were qualified to participate in the study. The average age of the patients in the study group was 63. The control group consisted of 15 patients who had not been previously treated for knee dysfunction, did not undergo surgery of the lower limbs and did not experience any discomfort at the knee joint. The presence of degenerative changes was confirmed during surgery in all subjects of the OA group. There is a significant age difference between the study group and the control group, which results from the fact that degenerative changes progress with the age of patients and surgery is the last form of treatment reserved for the most advanced changes. At the same time, joint
failure progresses with age; therefore, it would not be possible to create a control group of comparable age. Detailed characteristics of the group are presented in Table 1. The study received a positive opinion from the Bioethics Committee of the Medical University of Lublin consent number KE-0254/261/2019.

Table 1. Characteristics of study participants.

| Study group         | N   | Males/Females | Age (years ± SD) | Height (cm ± SD) | Weight (kg ± SD) | BMI   |
|---------------------|-----|---------------|------------------|------------------|------------------|-------|
| Controls (HC)       | 15  | 6/9           | 24.4 ± 6.0       | 170.7 ± 10.8     | 60.9 ± 11.1      | 20.7 ± 1.8 |
| Osteoarthritis (OA) | 13  | 4/9           | 63.6 ± 8.8       | 166.2 ± 7.4      | 91.3 ± 14.0      | 33.0 ± 4.4 |

2.2. Signal Acquisition
The measurement system was based on Arduino Mega2560 board. The signal was acquired using two analogue inputs from CM01B piezoelectric microphones. They are lightweight, robust and simple devices for use in detecting body sounds, stethoscopes etc. Their bandwidth spans from 8Hz to 2.2kHz. The sampling frequency was about 1400Hz with a 10-bit resolution. Additionally, a digital encoder was used to measure the knee position. To ensure patient safety a galvanic barrier was used on the USB connection and the device itself was powered using an 11.1V lithium-ion battery. The data was sent to the computer in ASCII format and recorded using RealTerm software.

2.3. Empirical Mode Decomposition
The EMD procedure proposed by Huang [28] is a data-adaptive technique used to decompose signals into components. It is a valuable tool used in signal analysis procedures, including nonlinear and non-stationary. This algorithm and its derivatives are used in vibroacoustic joint research [29,30]. EMD allows time-frequency processing on the original time scale, unlike wavelet analysis procedures. This algorithm involves dividing the recorded waveforms into components, called Intrinsick Mode Functions.
(IMF). The screening process is based on the determination of local extremes and their subsequent cubic spline interpolation to obtain the envelope for the minima and maxima of the waveform, respectively.

The mean of the lower and upper envelopes is then determined, allowing the so-called Prototype mode (proto-IMF) to be obtained. This function is considered an IMF when it meets two conditions: throughout the signal, the number of extremes and zero crossings is equal or differs by no more than one and the local mean (obtained from the envelope) is equal to zero. The sieving process is repeated n times until the specified stoppage criterion is met. The scheme of signal processing through EMD is presented in Figure 2.

2.4. Signal processing
Reports in the literature, e.g. [31], provide some information on the occurrence of frequency relationships between healthy knee joints and lesions. Procedures based on the EMD protocol can isolate, among other things, signal oscillations associated with the presence of chondromalacia or dysfunction of the anterior cruciate ligament (ACL). There are also known studies presenting the results of vibroacoustic analysis using a few selected indicators [27,32], or analyses in which the signal trend is removed [29].

To test the relevance and usefulness of selected indicators in knee diagnostic procedures, previously recorded time courses were analysed. The tests included the application of the EMD procedure to remove the signal trend and frequency filtering. The recorded waveforms were divided into IMFs from which those with normal distribution and physically meaningful distribution were extracted – in this case, these were IMFs 1–8. Due to a certain feature of EMD (i.e., the mode mixing phenomenon), the extracted signals were summed. The values of the indices were then determined: RMS, VMS, variance and signal energy. For both microphones located on the medial and lateral joint line in the control group (HC) and the group of patients diagnosed with osteoarthritis (OA) statistical analysis has been done.

2.5. Statistical Analysis
Statistical analysis to check whether there are significant differences between the mean values of the analysed indices: RMS, VMS, variance, signal energy between the study groups as well as between individual anatomical locations within the groups was performed using the Statistica package 13.3 (Tulsa, OK, USA). The significance level was taken to be $\alpha=0.05$. In order to check whether the interesting values of the selected indicators have distributions close to the normal distribution, three tests were used: Kolmogorov-Smirnov test, Lilliefors test and Shapiro-Wilk test. For indicators that do not have a normal distribution, the Mann-Whitney U test with a correction for continuity was applied [33]. This correction is applied to ensure that the test statistic can accept all values of real numbers according to the assumption of normal distribution.
3. Results
The results of the statistical analysis to check whether the individual indicators have distributions close to normal at the assumed significance level $\alpha=0.05$ showed that the values of the variables for the individual indicators of vibroacoustic signals do not have normal distributions; therefore, the Mann-Whitney U test with a correction for continuity was used in further analyses. The results of the obtained analyses are presented in Table 2.

**Table 2. Results of the Mann-Whitney U test with a correction for continuity.**

| Anatomical location | Indicator | Sum of ranks | Sum of ranks | U       | Z       | p       | 2*1str. |
|---------------------|-----------|--------------|--------------|---------|---------|---------|---------|
| Lateral             | RMS       | 94.00        | 341.00       | 3.00    | -4.41   | 0.000   | 0.000   |
|                     | Energy    | 182.00       | 253.00       | 91.00   | -0.55   | 0.584   | 0.589   |
|                     | Variance  | 94.00        | 341.00       | 3.00    | -4.41   | 0.000   | 0.000   |
|                     | VMS       | 94.00        | 341.00       | 3.00    | -4.41   | 0.000   | 0.000   |
| Medial              | RMS       | 144.00       | 291.00       | 53.00   | -2.21   | 0.027   | 0.025   |
|                     | Energy    | 209.00       | 226.00       | 90.00   | 0.59    | 0.554   | 0.559   |
|                     | Variance  | 144.00       | 291.00       | 53.00   | -2.21   | 0.027   | 0.025   |
|                     | VMS       | 147.00       | 288.00       | 56.00   | -2.08   | 0.037   | 0.036   |

For both lateral and medial sensors, statistical analysis at an assumed significance level of $\alpha=0.05$ showed statistically significant differences for indicators such as RMS, variance and VMS. A graphical summary of the results in the form of box-and-whisker diagrams for each anatomical zone is shown in Figures 3 and 4.

**Figure 3.** Summary of results for the sensor placed on the medial side a) VMS b) RMS c) variance d) energy.
Figure 4. Summary of results for the sensor placed on the lateral side a) VMS b) RMS c) variance d) energy.

The results of the statistical analysis to check for statistically significant differences between the values of individual indicators of vibroacoustic signals did not show any significant differences.

The most essential information provided by the graphs in Figures 3 and 4 is in the shape of the graphs. It very strongly suggests a large scatter of values in the HC group compared to OA. In the case of sensor location on the lateral side (3), we observe a large scatter of results relative to the range of 25–75% of observed values. For the medial side (1) there is also a wide variation in HC, but the observed results are more in the 25–75% range. For the OA group, we observe a much smaller scatter of values, with narrow ranges of 25–75% of observations. One of the diagnostic indicators tested is the RMS, a measure proportional to the amplitude, taking into account the time history of the waveform. It is particularly useful for oscillatory signals, with values differing in sign. For the medial side, we observe a greater dispersion of the values for the control group, while for the OA group there is less dispersion and a slight asymmetry in the area of most frequent observations. Much greater dispersion of RMS values is found in the data recorded from the lateral side: the scatter of values is more than 6 times greater for the OA group and about 6 times greater for the HC group. The median values and the range of the most frequent observations are located asymmetrically, closer to the minimum values. Very wide ranges are also found for the parameter of signal energy, both when recording at the medial and lateral side locations.

Differences are found here in the median position and the range of 25–75% of the observations. In the HC group, for the medial side, the graph is close to symmetrical, while for the lateral side there is a significant asymmetry with most observations being closer to the set maximum values. In the case of the OA group, there is a significant asymmetry for both the medial and lateral sides. In the case of the former, most of the observations are above the range mean, while in the latter they are below. The classic
measure of variability is variance. Its values are characterised by a significant scatter, occurring especially in the HC group. In the case of both test groups, the shape of the obtained graphs is asymmetric. The range of 25–75% of observations is closer to the minimum values, which may indicate individually obtained high values of the examined parameter. Graphs illustrating the VMS index, show similar features.

4. Conclusions
This paper presents an approach that uses the Empirical Mode Decomposition (EMD) algorithm to remove artefacts in VAG signals. The results obtained for RMS, variance and VMS, despite large, scatter, show statistically significant differences between the HC group and OA group for both analysed anatomical locations, which indicates their applicability in the non-invasive diagnosis of degenerative changes and confirms the possibility of assessing the degree of damage to joint surfaces based on generated vibroacoustic signals. A limitation of the study carried out is the small size of the test group; at this point, it is difficult to say whether the magnitude of the parameter scatter (especially in the HC group) was influenced by the individual studies in the group and the data set was too small or if it is related to the nature of the work of the intact joint. Further research with a larger group is needed to determine this. The need for more accurate methods to classify the condition of the knee joint, the much smaller scatter in the values of the indicators studied for the OA group could be due to one type of injury.

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