Estimation of differences in selected indices of vibroacoustic signals between healthy and osteoarthritic patellofemoral joints as a potential non-invasive diagnostic tool

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Abstract. Osteoarthritis (OA) is currently the most generic form of joint disease. It is a complex process in which degenerative changes occur in the articular cartilage [AC], subchondral bone, and synovial membrane and can lead to permanent joint failure. The primary and most commonly used method of diagnosing degenerative changes is classic radiography. Magnetic resonance imaging (MRI) may be used to assess the extent of damage to joint surfaces, but this method is limited by the availability of specialised equipment and the excessive cost of the examination. Arthroscopy, an invasive procedure, is considered the ‘gold standard’ in joint diagnosis. The occurrence of degenerative changes is closely related to the friction and lubrication processes within the joint. The main causes of osteoarthritis are a change or lack of synovial fluid, deformation of the joint bones, local damage to the articular cartilage, and a change in the mechanical properties of the articular cartilage due to water loss from the damaged superficial layer. An alternative, non-invasive method that allows for a delicate assessment of the condition of moving joints is vibroarthrography (VAG). The analysis of vibroacoustic signals generated by moving joint surfaces has an immense potential in the non-invasive assessment of the degree of damage to articular cartilage, meniscus and ligaments and the general diagnosis of degenerative diseases. The purpose of this study is to analyse and statistically compare the basic characteristics of vibroacoustic signals recorded with a CM-01B contact microphone placed on the patella for motion in the 90°–0°–90° range in a closed kinetic chain (CKC) in a control group (HC) and a group of patients diagnosed with osteoarthritis (OA), qualified for the knee alloplasty.

1. Introduction

As medicine develops, life expectancy increases and so does the need to ensure an adequate quality of life for patients. One of the most common causes of dysfunction in older people is degenerative changes in the knee joints [1,2]. The main structure involved in the degenerative process in the joints is the articular cartilage, which has the little regenerative capacity [3–6], making the degenerative process progressive. Furthermore, the knee joint, being the largest joint with an extremely developed internal
structure, is prone to injury. Although cartilage injuries are associated with an older population, they do not spare younger people. The causes of these changes include sports, work, genetics, musculoskeletal trauma, obesity, and even gender [7–10]. Advanced degenerative changes cause the progressive failure of the joint with the appearance of pain, reduced range of motion and stiffness. Due to the irreversibility of the process, it is extremely important to carry out a quick and accurate diagnosis of the joints to enable the introduction of treatment at an early stage of the disease and thus slow down its progress. Early detection of degenerative changes can help physicians apply appropriate therapeutic measures or decide to apply surgical treatment [11]. Apart from the general clinical examination, arthroscopy, imaging techniques and vibroarthrography (VAG) can be used in the diagnosis of cartilage pathology [11–13].

Typical imaging techniques such as X-ray, computed tomography (CT) and magnetic resonance imaging (MRI) can be used for the non-invasive assessment of knee joint disorders. The diagnosis of articular cartilage is complicated by the fact that it is not visible on conventional X-rays. Evident cartilage damage in the joint is visible on the X-ray indirectly as joint gap narrowing, subchondral sclerosis and osteophyte formation. However, these radiological signs are only visible at an advanced stage of the disease, making adequate joint-sparing treatment impossible. Conventional radiography is therefore used for surgical qualification or assessment of knee joint alignment but is not suitable for the early detection of potentially treatable cartilage lesions. The only non-invasive, dedicated method for cartilage assessment is the MRI [14]. However, MRI is an expensive, time-consuming examination with limited availability. Furthermore, the diagnostic performance in the assessment of articular cartilage is often unsatisfactory [15,16]. Therefore, modern medicine is looking for solutions to improve the diagnosis of degenerative changes, and thus allow the introduction of treatment at an earlier stage of the disease. One of the methods proposed for early, non-invasive diagnosis of the knee joint is vibroarthrography (VAG). The dynamic state of engineering objects can be evaluated by the vibroacoustic processes they generate [17–19]. During normal knee movements, both intra- and extra-articular components can produce vibrations or sounds as they move with each other. The signal that is emitted by the knee joint during flexion or extension is referred to as the VAG signal [11,20,21]. The change in mechanical properties, in particular, the appearance of bumps, cracks or cartilage defects in the successive stages of degenerative changes [22,23] affects the vibroacoustic image during movement of the knee joint. The available literature suggests that it is possible to reproducibly assess joint structures from the vibrations generated during joint movement. The evaluation of a joint based on changes in the acoustic signal generated dates back to the late 19th century when a method of locating free intra-articular bodies was presented based on auscultation with a stethoscope [24]. Similar phenomena were also observed in the early 20th century by other researchers [25]. At the beginning of the 21st century, research on the application of vibroacoustic in joint diagnosis began again. Advanced methods of acoustic signal analysis were introduced, such as adaptive time-frequency analysis [26], power spectral analysis [27] and high-frequency acoustic emissions. [28]. With the development of technology and signal analysis methods, the diagnostic efficacy of VAG in the diagnosis of the patellofemoral joint has been reported in the literature [29,30]. However, while the VAG is good at identifying disease states, there have been few publications to date that focus on the clinical application of vibroacoustic to diagnose the knee joint and, in particular, the patellofemoral joint. There are no standardised methods of examination or signal assessment. Thus, it is not known whether the use of vibroacoustic in diagnosis has sufficient sensitivity and specificity for different joint injuries to be more applicable in clinical practice. This study aims to analyse and statistically compare basic indices of vibroacoustic signals recorded with a CM-01B contact microphone placed on the patella for 90°–0°–90° movement in a closed kinetic chain (CKC) in a control group (HC) and in a group of patients diagnosed with osteoarthritis of the knee (OA), and to assess the potential use of selected indices in the non-invasive diagnosis of articular cartilage damage.

2. Materials and methods

2.1. Participants
The study was conducted on patients qualified for knee surgery due to previously diagnosed degenerative changes based on clinical examination and imaging studies. During surgery, degenerative changes were confirmed in all subjects in the OA group. The vibroacoustic assessment was performed the day before the scheduled surgery after informed consent was obtained from each patient. The control group in this study consisted of healthy volunteers who had not undergone any knee surgery, had not reported any joint complaints or been treated in any way for joint failure. The mean age in the study group was 65 years, while in the control group 30. The apparent age difference is since degenerative changes develop mainly in the elderly population, while only a small percentage of elderly people do not present any knee joint abnormalities. 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  |
|---------------------|----|---------------|------------------|------------------|------------------|------|
| Healthy control (HC)| 10 | 6/4           | 29.8± 9.0        | 176.1 ± 9.8      | 64.9± 11.3       | 20.8± 1.8 |
| Osteoarthritis (OA)| 10 | 3/7           | 65.3 ± 9.0       | 166.6 ± 6.1      | 93 ± 11.7        | 33.6 ± 4.7 |

2.2. Recording of Signals
The measurement system was based on Arduino Mega2560 board. The signal was acquired using one analogue input from a CM01B piezoelectric contact microphone. It is a lightweight, robust and simple device for detecting body sounds, stethoscopes etc. Its bandwidth spans from 8 Hz to 2.2 kHz. The sampling frequency used was about 1400 Hz 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.

Vibroacoustic signals were recorded with a CM-01B contact microphone placed on the patella for motion in the 90°–0°–90° range in a closed kinetic chain (CKC) in a control group (HC) and a group of patients diagnosed with osteoarthritis (OA), qualified for knee alloplasty.
2.3. Signal processing

The analysis of the signals for the recorded waveforms was carried out in two ways: in the first variant, the full range of movement of 0°–90° in the CKC was examined, while in the second, based on literature reports [31], the range was reduced to 25°–75° due to the possibility of strong signal disturbances in the initial and final phases of movement. Diagnostic indices such as mean, RMS, variance, kurtosis, crest factor, peak value, impulse factor, form factor and skewness were determined for both cases.

The wide range of diagnostic indices studied was intended to test their usefulness in the analysis of knee joint wear. Due to the lack of statistically significant differences between the tested ranges of 0°–90° and 25°–75°, the paper presents the results of statistical analysis for the range of motion 0°–90°.

2.4. Parameters’ selection

The selection of parameters for the study included the determination of the values of diagnostic indicators in HC and OA groups, and then determining whether there were statistically significant differences for a given indicator, which would confirm its potential usefulness in diagnosis. The first of the indicators examined was the arithmetic mean. It is one of the most popular, intuitive descriptive statistics. It provides information about the highest concentration of results in a selected set. The main imperfection of this measure is the fact that oscillating signals can assume values close to zero.

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$$  \hspace{1cm} (1)

Another indicator was the RMS value. This is one of the more commonly used, and more useful, parameters. It is a parameter proportional to the vibration energy and the probability of vibration damage. RMS considers the time history of the waveform and includes information about the magnitude of the amplitude. It is not sensitive to single pulses in the signal. It is expressed by the formula:

$$x_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} x_i^2}$$  \hspace{1cm} (2)

A parameter that characterises time courses well is the dispersion measure – variance. It provides information related to the amount of clustering of values in a sample. The larger it is, the more dispersed the results are concerning the mean. It is defined as:

$$s^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2$$  \hspace{1cm} (3)

Kurtosis may also be an indicator relevant to the diagnosis of knee joints. It is a parameter describing the degree of concentration of results in the distribution. It provides information about the degree of similarity of data scattered around the mean in relation to the normal distribution. The value of kurtosis for normal distribution is 3; in cases where the analysed distribution is more pointed this value will be higher, and for smaller values of kurtosis the distribution is flattened. It is a valuable parameter from the point of view of pulse detection in vibroacoustic signals. It is defined as:

$$x_{KUR} = \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^4 \left[ \frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2 \right]^2$$  \hspace{1cm} (4)

In vibroacoustic diagnostics, the crest factor is also a useful parameter. In analogy to machine diagnostics, it plays a special role in the initial stages of damage: strong impulses in the signal influence the size of the peak value parameter, while RMS may not change significantly for some time. CF changes with damage development in vibroacoustic signals: as damage develops, its high value starts to decrease. In vibroacoustic studies of joint surface damage, it may be relevant by analogy to its promising results in detecting bearing damage.

$$x_{CF} = \frac{x_{MAX}}{x_{RMS}}$$  \hspace{1cm} (5)
Due to the nature of knee vibroacoustic signals, the peak value may be of importance. This is the maximum value in the signal. The range of its usefulness includes mainly waveforms of impulsive character. In knee joint examinations, impulses can often appear when overcoming resistance to movement in the form of so-called “clicks.”

\[ x_{\text{MAX}} = \max(x) \]  

(6)

The impulse factor is a measure similar to the crest factor and expresses the relationship between the peak value and the mean value. Compared to CF, however, it shows greater sensitivity. It is defined as:

\[ x_{\text{IMP}} = \frac{x_{\text{MAX}}}{\bar{x}} \]  

(7)

The form factor may also be an interesting indicator. Its changes are influenced by the increase in deviation from the average value.

\[ x_{K} = \frac{x_{\text{RMS}}}{\bar{x}} \]  

(8)

From the point of view of knee joint diagnosis, skewness can also provide some information. This is the coefficient of asymmetry and is used to determine what the distribution looks like: is the data evenly distributed on either side of the mean or is there some variation.

2.5. Statistical analysis

Statistical analysis to check whether there are statistically significant differences between the individual parameters of the analysed vibroacoustic signals was carried out using the Statistica 13.3 package (Tulsa, OK, USA). The significance level was assumed to be \( \alpha=0.05 \). In order to check whether the variables of interest for the individual signal parameters have distributions close to the normal distribution, three tests were used: Kolmogorov-Smirnov test, Lilliefors test and Shapiro-Wilk test. The tests used to analyse equality of variance were F (Fisher’s), Levene’s, and Brownian and Forsyth tests. For the results characterised by the normality of distribution and equality of variance – the Student’s t-test was used for the analysis of equality of mean results for selected indicators of vibroacoustic signals at the assumed significance level. In the case of results characterised by the normality of distribution but non-uniformity of variance, the Student’s t-test with a separate estimation of variance (Cochran-Cox test) was used to analyse the equality of mean results of selected indicators of vibration-acoustic signals at the assumed significance level. [32]. For indicators that do not have a normal distribution, the Mann-Whitney U test with a continuity correction is applied to ensure that the test statistic can take all values of the 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 are summarised in Table 2. The analysis showed that in the OA group, variables for indicators such as Mean value, RMS, Crest factor, Peak value and Impulse factor do not have a normal distribution.

The variables for the other indicators in both OA and HC groups have a normal distribution. The results of statistical analysis for Student’s t-test and Student’s t-test with the separate estimation of variance (Cochran-Cox test) are summarised in Table 3. In the case of kurtosis, the assumption of homogeneity of variance is not met, the value of t-test for heterogeneous variances, i.e., t-test with separate variance estimation, should be considered, and for indicators such as variance, Waveform factor and skewness, the value of Student’s t-test should be taken instead. Statistical analysis at the assumed significance level of \( \alpha=0.05 \) showed statistically significant differences for indicators such as Variance (\( p=0.000 \)), Kurtosis (\( p=0.001 \)) and Waveform factor (\( p=0.000 \)). A graphical summary of the results obtained in the form of box-and-whisker plots is shown in Figure 2.
Table 2. Results of statistical analysis to test the normality of distribution.

| Study group       | N  | max D | K-S  | Lillief. | W     | p    |
|-------------------|----|-------|------|----------|-------|------|
| Mean              | OA | 10    | 0.26 | p > .20  | p < .05 | 0.82 | 0.03 |
| RMS               | OA | 10    | 0.29 | p > .20  | p < .05 | 0.75 | 0.00 |
| Variance          | OA | 10    | 0.18 | p > .20  | p > .20 | 0.97 | 0.85 |
| Kurtosis          | OA | 10    | 0.18 | p > .20  | p > .20 | 0.94 | 0.50 |
| Crest factor      | OA | 10    | 0.31 | p > .20  | p < .01 | 0.83 | 0.04 |
| Peak value        | OA | 10    | 0.43 | p < .05  | p < .01 | 0.51 | 0.00 |
| Impulse factor    | OA | 10    | 0.25 | p > .20  | p < .10 | 0.80 | 0.02 |
| Waveform factor   | OA | 10    | 0.17 | p > .20  | p > .20 | 0.97 | 0.88 |
| Skewness          | OA | 10    | 0.14 | p > .20  | p > .20 | 0.98 | 0.94 |
| Mean              | HC | 10    | 0.25 | p > .20  | p < .10 | 0.92 | 0.37 |
| RMS               | HC | 10    | 0.24 | p > .20  | p < .15 | 0.93 | 0.48 |
| Variance          | HC | 10    | 0.20 | p > .20  | p > .20 | 0.91 | 0.27 |
| Kurtosis          | HC | 10    | 0.20 | p > .20  | p > .20 | 0.86 | 0.08 |
| Crest factor      | HC | 10    | 0.25 | p > .20  | p < .10 | 0.91 | 0.27 |
| Peak value        | HC | 10    | 0.18 | p > .20  | p > .20 | 0.93 | 0.49 |
| Impulse factor    | HC | 10    | 0.13 | p > .20  | p > .20 | 0.96 | 0.81 |
| Waveform factor   | HC | 10    | 0.15 | p > .20  | p > .20 | 0.96 | 0.74 |
| Skewness          | HC | 10    | 0.24 | p > .20  | p < .15 | 0.91 | 0.28 |

Table 3. Results of Student’s t-test and Student’s t-test with the separate estimation of variance.

|                      | Mean OA | Mean HC | t    | P    | t sep. | df | p     | Standard deviation OA | Standard deviation HC | F quotient | p     | Levene's | p | Brn- Fors | p |
|----------------------|---------|---------|------|------|--------|----|-------|------------------------|------------------------|------------|-------|----------|---|----------|---|
| Variance             | 18902.34| 50817.70| -5.07| **0.000** | -5.07 | 16.07 | 0.000 | 11371.39 | 16323.85 | 2.06 | 0.296 | 2.68 | 0.119 | 1.74 | 0.204 |
| Kurtosis             | 3.67    | 1.98    | 4.11 | 0.001 | 4.11  | 11.98 | **0.001** | 1.20 | 0.50 | 5.87 | **0.015** | 5.95 | **0.025** | 4.61 | **0.046** |
| Waveform factor      | 1.09    | 1.20    | -4.28 | **0.000** | -4.28 | 17.98 | 0.000 | 0.06 | 0.05 | 1.06 | 0.927 | 0.09 | 0.773 | 0.08 | 0.775 |
| Skewness             | 0.10    | -0.08   | 1.58 | 0.132 | 1.58  | 11.49 | 0.142 | 0.33 | 0.13 | 7.09 | 0.008 | 4.93 | 0.039 | 5.14 | 0.036 |

For indices that lack normal distribution Mann-Whitney U-test with correction for continuity was applied; the results of statistical analysis are presented in Table 4. Statistical analysis showed statistically significant differences at the assumed significance level α=0.05 for indices such as Mean (p=0.003), RMS (p=0.000), Crest factor (p=0.005) and Peak value (p=0.001). A graphical summary of the results obtained in the form of box-and-whisker diagrams is shown in Figure 3.

Table 4. Mann-Whitney U test results with correction for continuity.

|                      | Sum of ranks OA | Sum of ranks HC | U    | Z    | p    |
|----------------------|-----------------|-----------------|------|------|------|
| Mean                 | 65.50           | 144.50          | 10.50| -2.95| **0.003** |
| RMS                  | 56.00           | 154.00          | 1.00 | -3.67| **0.000** |
| Crest factor         | 143.00          | 67.00           | 12.00| 2.83 | **0.005** |
| Peak value           | 59.50           | 150.50          | 4.50 | -3.40| **0.001** |
| Impulse factor       | 116.00          | 94.00           | 39.00| 0.79 | 0.427 |
In the majority of the studied statistics, the phenomenon of adopting wider ranges between the minimum and maximum mean values are observed in the OA group. As a result, it is more diverse in terms of the levels of indicator values obtained. Statistical analysis showed statistical significance for many of the parameters used. The mean value provides information about the concentration of results in the tested group. The comparison is shown above (Figure. 3) allows us to conclude that a higher concentration of results characterises the control group (HC). In the case of RMS, as well as peak value, we observe a significant asymmetry in the distribution of the OA group. The large deviation of the minimum values from the range of the most frequently observed values indicates a large variation in the magnitude of the amplitudes occurring in the OA group. Very wide ranges of the observed values and lower asymmetry in the distribution are characteristic of the crest factor and impulse factor. The large scatter of these values provides information on the internal variation in the degree of vibration signals emitted in the OA group, which in diagnostic terms may indicate a large internal variation of the group in terms of the degree of the occurring damage. Kurtosis describes the degree of concentration of the results in the distribution. In Figure 2 we can see a wider range of kurtosis values in the OA group. It is also worth noting that the kurtosis values themselves are larger for this group, which indicates differences in the shape of the distribution in this group. The skewness coefficient, as a measure of asymmetry, tells us how the results of a given variable are shaped around the mean. When comparing the two groups under study, it can be seen that the values of this indicator are also in the wider range for the OA group, which means that the values of the signals within this group are characterised by asymmetry. The variance is a classic measure of variability, its distribution in the HC group taking a shape indicating a slightly higher concentration of results in the group compared to OA.

**Figure 2.** Comparison of mean values of indices obtained for vibroacoustic signals a) kurtosis, b) variance, c) waveform factor, d) Skewness.
Figure 3. Comparison of mean values of indices obtained for vibroacoustic signals a) peak value, b) mean, c) impulse factor, d) crest factor, e) RMS.

4. Conclusions
The analysis of the obtained results showed the existence of statistically significant differences between the OA group and the HC control group for indicators such as Mean, RMS, Variance, Kurtosis, Crest factor, Peak value, and Waveform factor. This confirms their potential diagnostic usefulness and shows that based on generated vibroacoustic signals it is possible to assess differences in the state of joint cartilage damage. It is important to undertake further research into the specific types of joint damage occurring and their classification. The occurrence of wider ranges in the OA group may be related to the diverse types and locations of damage. The lack of an unambiguous classification of damage location influences the results, thus causing a large internal variation in the OA group.

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