A preliminary study on the use of EEMD-RQA algorithms in the detection of degenerative changes in knee joints

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Abstract. Degenerative changes, according to world literature, are one of the key reasons for disability, especially in the elderly population. Diagnosis and monitoring of the disease consist mainly in clinical examination, bedside interviews and imaging. However, during the healing process, there is currently no tool for fast, cheap, easily available and diagnostics that would be free from ionising radiation and that would enable evaluation of the course of the disease. Therefore, the scientific community is searching for new diagnostic methods, with the potential for wide application in medicine. Registration and analysis of knee joint vibration signals presents a chance for more accurate and faster diagnostics. The method is capable of detecting damage at an early stage, while specifying the selection of optimal treatment methods. Therefore, it seems crucial to develop methods of analysis appropriate for the nature of tested signals. The quality of low-frequency natural waveforms can be improved by filtration in selected bands, eliminating existing artefacts. This paper presents an application of the EEMD-RQA algorithm in the detection of degenerative changes in knee joints. Pre-processing in the form of filtration gives the opportunity to pre-test the usefulness of the algorithm RQA in the ability to create/subsequent development of indicators describing the condition of the joint surfaces examined without the need for surgical intervention.

1. Introduction

The knee joint is one of the biggest joints in the human body. Moreover, due to its unique location, it serves a vital role in a range of daily activities including work, leisure or sports. The main component of every synovial joint is the articular cartilage. The articular cartilage ensures smooth and painless movement between bones. Even though structures such as menisci, ligaments or synovial membrane protect the cartilage in motion, it is nonetheless subjected to high shearing and compressive forces, and its properties change during daily activities [1–3]. Moreover, if overused or after a traumatic episode, the forces in the cartilage may exceed its capacity and trigger an unstoppable chain reaction leading to osteoarthritis, which affects the biomechanical properties of the cartilage [4,5] and provokes pain and joint dysfunction. In 2010 osteoarthritis was the 11th most common cause of disability in the world, and research suggest that more and more people will be suffering from joint dysfunction due to osteoarthritis [6]. Also, the treatment of patients with degenerative changes generates substantial costs [7]. Total knee replacement is a gold standard in end-stage disease; however, every joint replacement has its limited
survival time. Especially young patients with osteoarthritis are susceptible to revision surgery, given that the 10-year survival rate of total knee replacement reaches 81%-92% [8]. One of the most important factors in prolonging joint endurance is the detection of early changes in the joint, which can induce osteoarthritis [9]. Orthopaedic surgeons have a variety of imaging modalities, which facilitate the detection of early osteoarthritis; however, each of these modalities has its weaknesses including radiation, examination waiting time or low sensitivity. None of the existing techniques such as computed tomography, conventional radiography, MRI or ultrasound, can be implemented on a larger scale as a screening evaluation. Requirements such as low costs, reproducibility, diagnostic accuracy or wide availability might be met by vibroacoustic analysis of signals emitted by joints during movement. With the advancement of imaging techniques, there has been progress in the field of medical signal [10,11] and image [12] processing methods. The method is non-invasive, simple, reproducible, cost-effective, and yet to date, it has not been implemented in medicine on a larger scale. This article presents the vibroacoustic analysis that can be a helpful tool supporting objective evaluation of arthrokineematic motion quality and detection of osteoarthritic changes in knee joints. Analysis of vibroacoustic processes generated by the knee joint in contrast to classical diagnostic methods provides detailed information on the tribological properties of the joint, associated, among others, with the state of the vitreous cartilage and rheological properties of the synovial fluid [4,13].

Vibroarthrography provides an opportunity to quantitatively and objectively evaluate the integrity and smoothness of the articular cartilage during joint motion. As shown before, vibroacoustic signals generated by a damaged articular cartilage might show specific properties that can be used in the detection of articular cartilage abnormalities [14,15]. Moreover, the signals generated by an abnormal cartilage have been shown to correspond with the degree of cartilage damage [16]. Some authors suggested that osteoarthritic changes in joints produce vibroacoustic signals of higher frequency, greater peaks and elongated duration in comparison to the healthy knee joint [17]. It is believed that evaluation of vibroacoustic emission adds insight into tribological properties of the joint, and reflects the articular cartilage and synovial fluid status [18], which in turn reflect the clinical appearance and the function of the articular cartilage, thus affecting the treatment regimen [19]. The vibroacoustic analysis is suggested as a complementary evaluating method in addition to imaging modalities such as MRI, ultrasound or conventional radiography [10]. However, to date no standards regarding equipment, testing routine or data processing have been established. Furthermore, the literature shows lack of consensus with respect to the examination protocol, whether it should be conducted in an open or a closed kinematic chain [20]. Therefore, further investigation of the subject is required in order to establish repeatable and reliable examination conditions, which could provide researchers with comparable results in order to set guidelines for further testing and preparation of commercial diagnostic devices.

The article presents the results of preliminary tests on the application of EEMD (Ensemble Empirical Mode Decomposition) and RQA (Recurrence Quantification Analysis) algorithms as potential tools in the detection of degenerative changes occurring in the knee joint.

2. Methods
The results were obtained from tests performed on two volunteers: one with healthy knee joints and the other one with diagnosed chondromalacia in both knees. The clinical appearance of the chondromalacia was evaluated with the visual analogue scale (VAS), which is a validated method of subjective pain assessment. The test session included slow knee extension in a sitting position (open kinetic chain) and rising up from chair (sit-to-stand) movements (closed kinetic chain). During the test session, both knees were independently tested. The acoustic signal was measured using an analogue contact microphone CM01b connected to a National Instruments data acquisition card. The signal was sampled at 1kS/second for 30 seconds. The analogue to digital converter resolution was set at 16 bits. At 5V reference voltage, this resulted in about 76 microvolts resolution. The recorded data have been subjected to signal analysis. The studies were connected with RQA (Recurrence Quantification Analysis) preceded by EEMD (Ensemble Empirical Mode Decomposition) filtration methods used for acquired bioacoustic signals. Four intrinsic mode functions (IMF) were extracted from the input signal to allow further
analysis, by removing irrelevant frequency components. The RQA tests were performed to compare bioacoustic signals generated by healthy and diseased joints. The signal processing graph of EEMD-RQA method is presented below.

Adaptive technique Empirical Mode Decomposition (EMD) is a tool in the time-frequency analyses of nonlinear and non-stationary signals [21–23]. The basic assumption of this algorithm is to decompose the signal into a finite number of mode oscillations imbedded in the input signal known as Intrinsic Mode Functions (IMFs). EMD analyses have found a wide range of applications [24,25].

EMD algorithm is based on the process of sifting the IMFs from given input data set. IMF acquisition is related to local extremes identification. The found local maxima are interpolated by cubic spline in order to build the upper signal envelope. The same procedure is followed for the determination of the lower envelope. Subsequently, at each point their mean \( m_1(t) \) is calculated along with the difference between the input data \( x(t) \) and \( m_1(t) \):

\[
h_1(t) = x(t) - m_1(t)
\]

Function \( h_1(t) \) is an IMF when it satisfies two conditions [21]:

- In the whole data set, the number of extremes and the number of zero crossings must be either equal or differ at most by one.
- At any point, the mean value \( m_1(t) \) of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

Sifting procedure is repeated \( k \) times, where \( h_0(t) \) is taken as input data:

\[
h_n(t) = h_{n-1}(t) - m_n(t)
\]

The process can be stopped when the condition of equality of the zero crossings and extremes number is fulfilled. Then it is determined a residual signal \( r_n(t) \), described as:

\[
r_n(t) = x(t) - \sum_{i=1}^{n} c_i(t)
\]

where \( c_i(t) \) is an \( i \)-th Intrinsic Mode Function and \( n \) expresses the largest number of mode oscillations possible to obtain.

![EEMD-RQA method](image.png)

**Figure 1.** EEMD- RQA method.

The algorithm used in the study, EEMD, differs from EMD by white noise implementation. Additional white noise is helpful to force the ensemble to exhaust all possible solutions in the sifting process. In the case of the realised research, EEMD algorithm is used to place a signal portion in the IMF areas of the same scale.

Recurrence Quantification Analysis is one of the methods for analysing nonlinear dynamic systems. The inference on RQA coefficients is based on dependencies occurring at recurrence plots [26,27]. The recurrence rate (RR) parameter defines the density of recurrence points and the number of recurrences. RR informs about the probability of recurrence in a measured system. Determinism (DET) parameter
focuses on the number of recursive points forming linear segments parallel to the main diagonal line on RP (recurrence plot). It measures the degree of determinism of the analysed phenomenon. The coefficient describing the complexity of the deterministic structure in the system is known as Entropy (ENTR). Laminarity (LAM) is the measure of system behaviour stability. The last parameter used in the current analysis was trapping time (TT) parameter, which refers to the average length of vertical lines measuring the time scale of changes occurring in the studied process.

3. Results
Figures 2 and 3 show waveforms registered in opened and closed kinematic chains. There 5 movement cycles were executed for the healthy knees and for the dysfunctional ones.

![Figure 2. Waveforms registered in an opened kinematic chain.](image1.png)

![Figure 3. Waveforms registered in a closed kinematic chain.](image2.png)

Pre-processing included the EEMD filtration procedure. The results obtained for the opened kinematic chain are shown in figures 4 and 5.
Figure 4. EEMD results: opened kinematic chain, joint with chondromalacia.

Figure 5. EEMD results: opened kinematic chain, healthy knee joint.

Closed kinematic chain results for healthy and damaged knee joint surfaces are placed in figures 6 and 7.
EEMD allowed obtaining 15 IMFs as a result of the sieving process. Low- and high-frequency components were separated, low-frequency signals were analysed more closely. Due to the lack of relevant diagnostic information that would provide the introduction of pathological changes contained in IMF 1-3, they were not included in further analyses [28].

In the case of degenerative changes for the open kinematic chain, higher amplitudes of oscillations at higher frequency ranges (IMF 4) are observed. However, at lower frequencies, higher amplitude values are noted for healthy knee joints. It is connected with the occurrence of vibrations coming from the muscle tension and vibrations of the ligament apparatus.

Recurrence Quantification Analysis has shown significant differences between healthy and degenerated joints. The largest variations were observed in the case of the Trapping Time parameter.

Figure 6. EEMD results: opened kinematic chain, knee joint with chondromalacia.

Figure 7. EEMD results: opened kinematic chain, healthy knee joint.
For open kinematic chain movements, the discrepancies reach 35% and 30% for closed kinematic chain movements. RQA results are presented in Table 1.

Table 1. Recurrence Quantification Analysis: ChO- chondromalacia, opened kinematic chain; HO- healthy, opened kinematic chain; ChC- chondromalacia, closed kinematic chain; HC - healthy, closed kinematic chain.

| Type   | RR   | DET  | ENTR | LAM  | TT   |
|--------|------|------|------|------|------|
| ChO    | 127.500 | 99.996 | 8.159 | 99.997 | 196.306 |
| HO     | 80.211  | 99.969 | 7.030 | 99.983 | 70.267  |
| ChC    | 86.245  | 99.980 | 7.511 | 99.988 | 124.636 |
| HC     | 65.757  | 99.967 | 6.946 | 99.982 | 43.623  |

4. Conclusions
The initial analysis has shown the existence of significant differences in the readings obtained from healthy and damaged knee joints. The obtained results clearly indicate the great importance of the TT parameter in RQA. Longer TT for joints with chondromalacia could point to the necessity of extending the movement time with a view to countering pain. The analysis of vibroacoustic processes generated by the knee joint is a high-precision objective tool for the assessment of the quality of the performed joint articulation. The non-invasive and low-cost character of the method enables its application in monitoring the condition of joint structures. Bioacoustic signal analysis methods are a promising area for further research. Future investigations ought to engage a more numerous group of patients combined with an intraoperative assessment of the degree of damage to the articular cartilage.

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