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EVALUATION OF SAVITZKY-GOLAY FILTERING APPLIED TO VIBROARTOGRAPHIC SIGNALS ACQUIRED AT THE KNEE LEVEL AND ITS IMPACT ON THE CREST FACTOR

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Abstract: *Arthrosis is a degenerative disease that affects the vast majority of the population, especially the elderly and overweight people. Often the condition is diagnosed in its advanced stages when pain and swelling appear. The diagnostic methods currently used are largely invasive and not standardized. Non-invasive and standardized methods are needed for the vibroartographic (VAG) diagnosis of this disorder, requiring new signal processing methods for denoising and selecting useful features of the VAG signal. Therefore, this paper aims to review current diagnostic methods, analyze the viability of Savitzky-Golay filtering and the Crest factor in separating abnormal from normal knee joint status for a database of eighty-nine signals reported in the literature, and outline future research directions for the development of a viable technique that can be used to diagnose osteoarthritis in new, non-invasive ways. Our findings prove that SG filtering and the Crest factor cannot separate normal and abnormal VAG signals, as previously suggested by some authors. Analysis of the Calgary confident database, which is widely validated in the literature, could help us in mapping new effective research directions.*
Key words: *knee joint, osteoarthrosis, diagnosis, vibroacoustic signal, non-invasive method.*

1. INTRODUCTION

Osteoarthrosis (OA) is a chronic condition characterized by degenerative changes in various structures of a joint, including bones, cartilage, ligaments, menisci, and synovial tissues. It is a prevalent joint disorder that affects the joint as a whole, leading to significant functional impairments. The incidence of OA increases with age, and important risk factors include obesity, gender (with women being more susceptible), daily activities, and occupation. Given its exponential growth in recent years, OA has become a major public health concern, impacting patients' lives and having notable socioeconomic implications [1].

Although OA can affect any joint in the body, the knee joint is particularly susceptible due to its multiple functions and location [2] [3]. Clinical manifestations of OA include pain, swelling, restricted range of motion, morning stiffness, joint deformity, and the presence of coarse crepitus [4] [5].

Currently, the diagnosis of OA relies heavily on invasive methods and the expertise of clinicians conducting evaluations [6]. These diagnostic approaches are standardized but still require subjective judgment and experience.

Overall, OA presents a significant challenge in terms of diagnosis, and there is a need for more advanced and non-invasive techniques to improve accuracy and provide early detection of the condition.

2.CURRENT METHODS FOR DIAGNOSIS

When diagnosing OA, the initial assessment relies on clinical signs, symptoms, and risk factors. However, these factors alone do not provide a definitive diagnosis. Therefore, additional methods are employed to confirm the preliminary diagnosis [5] [7] [8].

Imaging tests, including X-rays, magnetic resonance imaging (MRI), and computed tomography (CT), play a crucial role in the diagnostic process. Conventional radiography is commonly used but has limitations in visualizing non-osseous structures, and cartilage loss can only be indirectly inferred. MRI allows for a comprehensive evaluation of the joint, enabling a more accurate diagnosis compared to radiography. However, it may involve the use of a contrast agent, which is not suitable for all patients, and it can be costly. CT, along with MRI, can be utilized when radiography fails to provide sufficient information. CT offers advantages such as faster scanning times, wider availability, and lower cost. Nonetheless, it involves radiation exposure, which means the method is invasive [7] [9] [10] [11].

Ultrasound is another valuable tool in confirming the diagnosis of OA. It is a convenient and comfortable option for patients. Ultrasound allows visualization of various tissues around the affected joint; however, it relies on the skill of the operator, and measurements, such as cartilage thickness, may vary depending on the operator's technique [10] [12].

In addition to imaging tests, laboratory tests can be conducted to rule out other conditions and provide supplementary information. Although there are no specific tests that directly indicate the presence of OA, blood tests, such as complete blood cell count, erythrocyte sedimentation rate, C-reactive protein, and synovial fluid evaluation, can aid in differentiating between types of arthritis. Synovial fluid analysis requires the insertion of a needle into the affected joint to collect fluid for microscopic examination [13].

While arthroscopy is considered the gold standard for OA diagnosis, its invasiveness and limited efficacy have led to a decline in its use [14] [15].

The development of novel methods for arthrosis diagnosis can be approached through two distinct avenues: focusing on the equipment and devices used for data acquisition or prioritizing the post-processing of acquired signals. This paper aims to review current diagnostic methods, evaluate Savitzky-Golay filtering and the Crest factor's effectiveness in distinguishing normal from abnormal knee joint status using eighty-nine signals from existing literature. It also outlines future research directions for developing a non-invasive technique to diagnose osteoarthritis.

3. VIBROARTOGRAPHY FOR DIAGNOSIS OF OSTEOARTHROSIS

As mentioned before, in cases of OA, a crepitus sound is present at the joint level, even in incipient phases.

VAG signals are acquired during joint movements on the knee (flexion and extension). These vibroacoustic signals are post-processed and various parameters are extracted, trying to differentiate between the different states of the knee joint. The components and hardware parts of this type of analysis must be placed on articular surfaces, in contact with the skin, assuring that crepitus sounds of the joint are maximized, while the artifacts, minimized. The location is, therefore, very important to the signals acquisition, as the VAG signals change accordingly to the position. Multiple papers have shown that the ideal placement is on the medial compartment, below the midline of the patella [15].

When facing biomedical systems or developing new techniques for medical applications, the signal and its noise have a major impact upon the final results. Noises and artifacts are almost always contained within the acquired data, therefore, there is a high need for the signals to be filtered and processed accordingly to the type of application. These noises can come from either interfering signals from the body (muscles movement), movement of the equipment upon the skin or even from the device itself (thermal effect of circuits), or the movement of body segments when the patient is asked to perform flexion-extension of the knee. Removal and post-processing of signals is a crucial step in practical application in order to develop reliable systems that can be used in spite of these artifacts [15] [16] [17].

Many studies have focused their attention on developing methods to remove these artifacts from the raw acquired data. For example, [17] described a cascade moving filter that was able to aproximate the baseline wander in the signals, showing good results in using this method. Many papers [18] [19] [20] have focused their attention on using Fourier transform to filter and classify these signals, showing generally promising results.

The field of Vibroarthrographic (VAG) signal processing remains relatively nascent, and its efficacy in detecting early-stage knee arthrosis is often limited. Several studies have proposed the utilization of Savitzky-Golay (SG) filtering to enhance VAG signal analysis. Our objective is to develop a machine learning algorithm capable of automatically classifying VAG signals into normal and abnormal categories. To achieve this, we need to delineate a robust method for segregating normal and abnormal VAG signals, primarily relying on the identification of pertinent statistical parameters. Crest factor, a widely endorsed statistical parameter in the literature, will play a central role in this endeavor.

To facilitate the development and validation of our algorithm, we are leveraging the extensively utilized Calgary database [32-34], a valuable resource for assessing and validating novel signal processing techniques. This database will serve as a crucial foundation for our work, enabling us to create a reliable software tool capable of processing our own acquired VAG signals, which may potentially exhibit suboptimal data quality due to equipment limitations or elevated levels of noise.

Fig. 1. shows how the SG filter works for a simple model of data filtering, in which a random signal was generated, then smoothed using sgolayfilt sintax. The polynomial order was set to 5 with a frame length of 13 [22].

Mathematically, the Savitzky-Golay filter is based on polynomial fitting and least-squares regression [23] [24].

3.1 Savitzky-Golay Filter

Savitzky-Golay (SG) filter is a good method to use when in need to smooth a signal, with the advantages that it can track signal closely and accounts for transient effect, and also because it preserves high frequency components of data. SG filter has been widely used and known and works as a low-pass filter for signals and image processing. Its main advantages are: the ability to keep important details of signal’s curves, while also effectively removing noise [21].

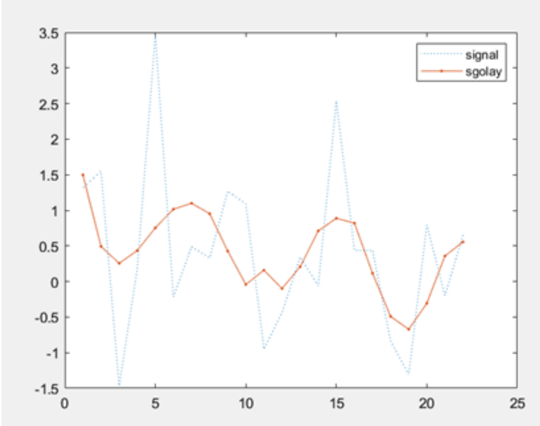

Fig.1. Example of SG filter

Few authors have used the SG filter to work with the knee signals obtained, showing good results, when associated in different types of algorithms, with more than one techniques, but there are also authors that have denied that the SG would be suited to be used with VAG signals, although it can be used with different types of biomedical signals, such as EEG or ECG [25] [26] [27] [28].

In [29], the authors proposed a denoising method that uses a 3rd order SG filter with 41 frames, along with other steps (such as a 10th order Butterworth filter, empirical decomposition) and have obtained good results and accuracy in filtering the signals, but with a slower response, which should not necessarily be an issue, as the diagnosis of osteoarthrosis is not time-critical.

In a proposed invention, [30] authors have developed an invention based on a wearable system for knee joint overall health assessment, in which they have used the SG filter Signal Smoothing: The Savitzky-Golay filter of 4th order and 21 taps was applied to smooth the signal obtained from the knee.

After applying the matched filtering approach, the resulting signal was also differentiated using a Savitzky-Golay filter of the same kind as used for the smoothing step. Differentiation is used to emphasize changes in the signal, particularly abrupt changes or peaks. By differentiating the signal, the authors aimed to enhance the characteristics associated with heartbeats, making it easier to detect and analyze them accurately.

3.2 Statistical processing results

Statistical parameters such as Crest factor, mean, standard deviation, skewness, kurtosis, and waveform features like amplitude, duration, and rise time can be calculated. These parameters provide insights into the overall characteristics and variations of the VAG signals.

- Mean: It represents the average value of the signal over a given time interval and provides information about the baseline or overall magnitude of the signal.

$$\mu = mean(x) = \frac{1}{N} \cdot \sum_{i=0}^{i=N-1} x_i \qquad (1)$$

- Root mean square (RMS) of the VAG signals: provides a quantitative measure of the overall signal amplitude and variability. Calculating the RMS of VAG signals allows for the assessment of signal stability and the identification of any abnormal fluctuations or irregularities.

$$RMS = \sqrt{\frac{1}{N-1} \cdot \sum_{i=0}^{N-1} \left(x_i^2 - \mu^2\right)} \qquad (2)$$

- Crest factor: The crest factor is a useful parameter in time-domain analysis of VAG signals, providing insights into the peak amplitudes and amplitude variations within the signals. This factor includes both peak amplitude and RMS variation of the VAG signals [31].

$$Crest\ Factor = \frac{Peak\ Amplitude}{RMS\ Value} \qquad (3)$$

In VAG analysis of knee joint signals, the crest factor can provide valuable information about the dynamics and variations in the joint's vibrational behavior.

A high crest factor indicates that the signal has large peak amplitudes relative to its average level. This implies that the signal contains significant transient or impulsive components with short-duration high-energy events. On the other hand, a low crest factor suggests a more evenly distributed and smoother signal without pronounced peaks.

4. RESULTS AND DISCUSSIONS

The decision to employ Crest factor as a filtering method was motivated by its capability to encompass important statistical measures such as the Root Mean Square (RMS) value and peak amplitude. By considering these aspects, Crest factor offers a more comprehensive approach to signal analysis.

To assess the effectiveness of Crest factor, experiments were conducted on signals extracted from both normal and abnormal patients. The data used in these experiments were obtained from the Calgary database [32] [33] [34].

In Fig. 2., the results obtained from the application of Crest factor to the signals without any additional filtering are presented. It is important to note that no preprocessing or denoising techniques were applied to the data prior to the analysis. Both normal and abnormal signals were subjected to the analysis to determine whether the Crest factor could effectively differentiate between these two categories. These results provide insights into the performance and potential of Crest factor in distinguishing between normal and abnormal signals within the studied database.

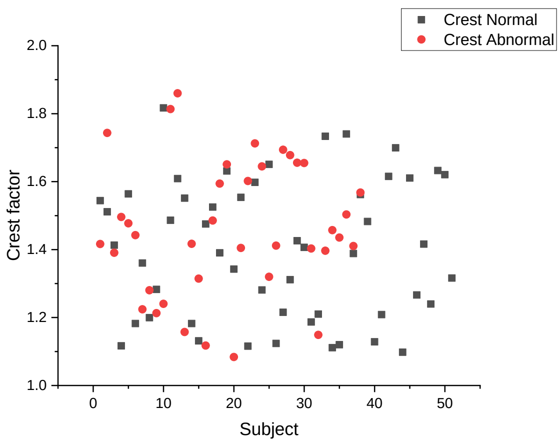

Fig.2. Results after applying Crest factor on the signals from the available database for normal and abnormal signals

In Fig. 3., a Savitzky-Golay (SG) filter with a specific configuration was applied to the signals. The chosen filter order was 3, and the frame length used was 41, following the recommendation provided by [29]. The purpose of applying this filter was to investigate its impact on the efficacy of the Crest factor in distinguishing between abnormal and normal signals.

The current approach of using SG filtering and Crest factor as extraction methods for VAG signals appears to be inadequate for future analysis. In order to enhance the denoising process of VAG signals, more sophisticated techniques such as Empirical Mode Decomposition (EMD) and Improved EMD (IEMD) need to be explored. These methods offer a higher level of complexity and sophistication, enabling better noise reduction. Once the denoising stage is complete, it becomes imperative to identify a suitable feature extraction technique for the VAG signals. Options like wavelet transform and minimal entropy analysis hold promise in this regard. These techniques possess the capability to capture important characteristics and patterns in the signals.

To further enhance the analysis and interpretation of VAG signals, it is essential to harness the power of machine learning. Employing artificial neural networks and reinforcement learning algorithms can aid in effectively analyzing and categorizing the VAG signals based on their normal or abnormal nature.

Contrary to existing literature, the findings presented in this study demonstrate that relying solely on the Crest factor does not yield a noticeable differentiation between normal and abnormal VAG signals. Even when combined with the SG filter, the Crest factor fails to provide valuable insights into the distinguishing features of VAG signals from normal and abnormal patients. Therefore, there is a need to explore more advanced and comprehensive approaches for the accurate characterization and classification of VAG signals.

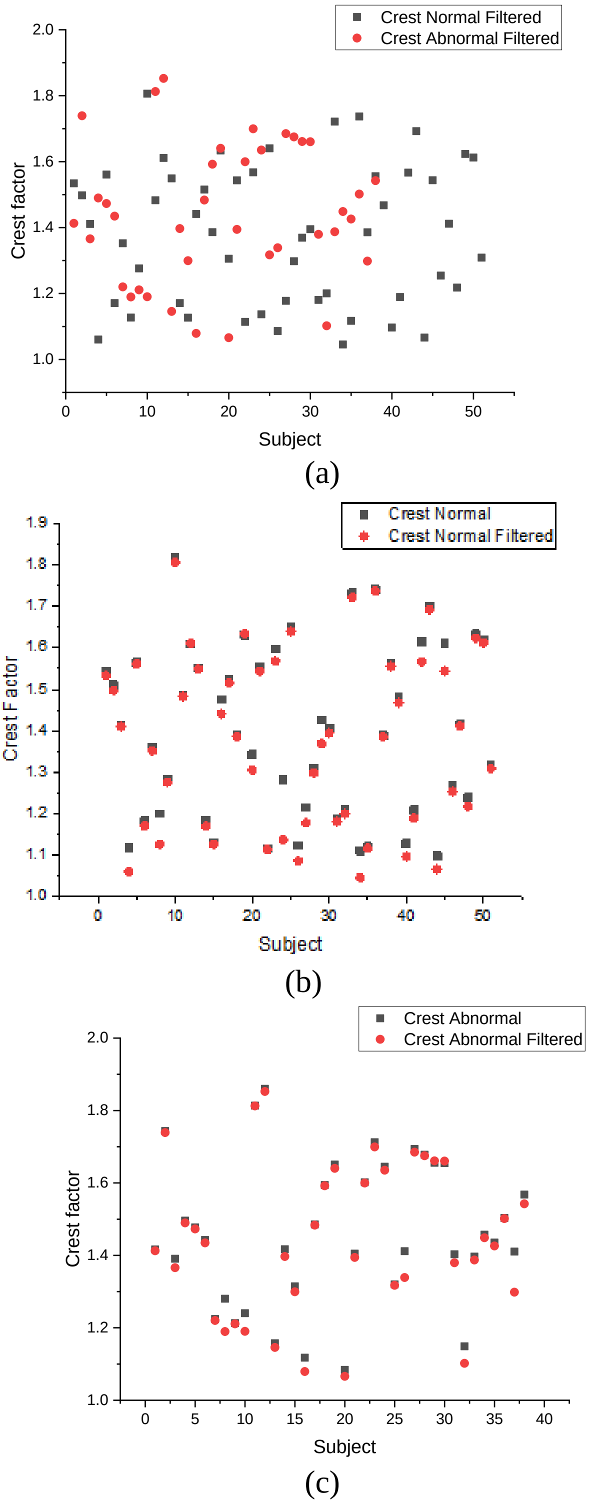

Fig.3. Results obtained after SG filtering and Crest factor. a- distribution of results on both normal and abnormal signals with SG filter applied; b-normal signals, with and without SG filter applied; c-abnormal signals, with and without SG filter applied

To facilitate the development and validation of our algorithm, we are leveraging the extensively utilized Calgary database [32-34], a valuable resource for assessing and validating novel signal processing techniques. This database will serve as a crucial foundation for our work, enabling us to create a reliable software tool capable of processing our own acquired VAG signals, which may potentially exhibit suboptimal data quality due to equipment limitations or elevated levels of noise. Recognizing that the existing literature has, in some cases, led us down a less fruitful path in our quest to create an effective (VAG) diagnosis tool, it is imperative to acknowledge the significance of our negative findings. Such outcomes can play a pivotal role in conserving the valuable time and resources of fellow researchers in the field. Our research endeavors have not been in vain, as the insights gleaned from our results have opened up exciting avenues for further exploration. These new research directions encompass alternative methodologies, notably the exploration of enhanced empirical mode decomposition (EMD) techniques for denoising VAG signals. This approach holds promise for improving the quality of our data and, subsequently, the accuracy of our diagnostic tool. Furthermore, we are venturing into the realm of machine learning as a means of developing more sophisticated algorithms for the classification of VAG signals. Machine learning approaches are particularly encouraging, offering the potential to extract meaningful information from inherently noisy knee-level signals. These avenues of inquiry are poised to bring about significant advancements in the field of VAG diagnosis, marking a positive shift in our research trajectory.

5. CONCLUSIONS

The evaluation of the effect of Savitzky-Golay (SG) filtering applied to vibroartographic (VAG) signals specifically at the knee level has been undertaken to analyze its impact on the Crest factor. This investigation seeks to understand how the application of SG filtering, a commonly used signal processing technique, affects the Crest factor in VAG signals acquired at the knee level.

The diagnostic methodologies for VAG signals have been underscored in alignment with contemporary guidelines. VAG signals, obtained from a renowned database at the University of Calgary [32-34], which is globally esteemed for the evaluation of emerging signal processing techniques, underwent denoising via SG filtering and were subsequently classified utilizing the Crest factor. However, the filtering proved to be inefficient in this statistical processing. Filtering the signal originating from the knee is challenging due to signals being obscured by noise originating from variations in cartilage thickness, other biological noises, and subject-specific variations.

To improve the quality of VAG signals obtained from the knee, alternative methods, including denoising by improved empirical mode decomposition techniques (EMD), should be explored. Additionally, machine learning approaches hold promise in developing better algorithms for classifying VAG signals and extracting meaningful information from noisy knee-level signals.

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Tehnică de prelucrare a semnalelor pentru diagnoza vibroartografică (VAG) a artrozei articulației genunchiului

Artroza este o boală degenerativă care afectează marea majoritate a populației, în special persoanele în vârstă și persoanele supraponderale. Adesea, afecțiunea este diagnosticată în stadii avansate, atunci când apar durerile și umflăturile. Metodele de diagnosticare utilizate în prezent sunt în mare parte invazive și nu sunt standardizate. Sunt necesare metode neinvazive și standardizate pentru diagnosticarea vibroartografică (VAG) a acestei afecțiuni, fiind necesare noi metode de procesare a semnalului pentru diminuarea influenței zgomotelor și selectarea caracteristicilor utile ale semnalului VAG. Prin urmare, această lucrare își propune să treacă în revistă metodele actuale de diagnosticare, precum și să propună un algoritm eficient de procesare a semnalului, reprezentând o tehnică viabilă care poate fi utilizată pentru a diagnostica osteoartrita în moduri noi, neinvazive. Pentru a valida algoritmul propus și pentru a evidenția eficiența acestuia, a fost utilizată o bază de date universală.

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