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Correlation between Linear and Non-Linear Vibroartrographic Parameters

Streszczenie. *W niniejszej pracy autorzy porównali liniowe i nieliniowe cechy wibroartrogramu (VAG) w kontekście stawu kolanowego. W badaniuwzięło udział 220 zdrowych uczestników, podzielonych na pięć grup wiekowych (trzecia, czwarta, piąta, szósta i siódma dekadażycia). Cztery cechy˙ liniowe (tj. wariancja średnich kwadratów, amplituda i dwa parametry częstotliwości) oraz dwie cechy nieliniowe (tj. wieloskalowa entropia i częstość nawrotów) były ze sobą skorelowane. Korelacje w obrębie grup liniowych i nieliniowych okazały się dodatnie, natomiast korelacje międzygrupowe okazały się ujemne. Również w kontekście zróżnicowania wieku cecha częstości nawrotów okazała się najbardziej informatywna.* ***(Korelacja między Liniowymi a Nieliniowymi Parametrami Wibroartrograficznymi)***

Abstract. *In this paper the authors compared linear and non-linear features of the vibroarthrogram (VAG) in knee joint context. There were 220 healthy participants in the study, divided into five age-related groups (third, fourth, fifth, sixth and seventh decade of life). Four linear features (i.e. variance of the mean squares, amplitude, and two frequency parameters) and two non-linear features (i.e. multi-scale entropy and recurrence rate) were correlated with each other. Correlations within linear and non-linear groups proved to be positive, while inter-group correlations turn out to be negative. Also, in the context of age differentiation, recurrence rate feature proved to be the most informative one.*

Słowa kluczowe: przetwarzanie sygnału, wibroartrografia, parametry liniowe, parametry nieliniowe
Keywords: signal processing, vibroartrography, linear parameters, non-linear parameters

Introduction

Over the last 30−40 years life quality and duration have significantly improved [1-9]. Due to these and also due to the decreasing births number in highly developed countries causes rapid society ageing [2, 4, 6, 10]. As age-related physiological processes it is possible to consider joints and their ligaments elasticity loss and capsular fibrosis [2-5, 7].

Proper medical diagnosis leads to proper therapy, however the standard diagnosis is usually limited to traditional imaging methods and subjective medical interview and physical examination [2, 11- 16]. Unfortunately, all imaging methods, including those more sophisticated and expensive, unable quality of joint motion observation [2, 12, 14, 16].

One of a few methods applied for the purpose of joint condition assessment is vibroarthrography (VAG), which works in a way that vibroacoustic signals generated by motion of the articular surfaces are registered [2, 17, 18, 19, 20]. Thus, the VAG signals registered from abnormal joints possess different waveform pattern while compared to the healthy ones [2]. It makes the vibroartrography a tool, which enables precise and objective quality of movement in the joint assessment. This method is also non-invasive and allows to monitor the effects of treatment or rehabilitation of joint structures [2, 20, 15].

Impaired quality of joint motions is frequently associated with various articular surfaces disorders. As clinical sign of these – crepitations are being considered [21, 20]. Biomechanical and morphological alteration may result in cartilage degeneration, which are frequently manifest with crepitus during joint motion [22]. Therefore it is possible to apply VAG for the purpose of knee joints degeneration level based on vibroacoustic emission in disease-affected joints [22, 20].

One of the most heavily stressed joints in the human body are the knee joints, which results in their increased susceptibility to injuries or damage. The knee joints are also prone to premature degeneration of the articular surface [23, 24]. One of the most complex joints is patellofemoral joint (PFJ) [24, 25, 26]. Diseases related with the PFJs are also one of the most challenging [26]. Nowadays, the most popular joint motion assessment methods are quantitative methods limited to goniometer or arthrometer, while their qualitative analysis still has some limitations [24].

In this paper the authors focused on both linear and nonlinear vibroartrography (VAG) parameters applied for the purpose of knee joint condition assessment. The VAG is a noninvasive method for sensitive and objective articular function assessment; it is based on high frequency vibroacoustic emission analysis, and as damaged cartilage cause greater friction and VAG signal amplitude and frequency increased – it is useful for diagnostic purposes [27]. The authors of this work tested both linear and non-linear VAG parameters and compared them.

Study Participants

The study group consisted of 220 healthy individuals – 127 females and 93 males, divided into five age-related groups (see: Table 1): third, fourth, fifth, sixth and seventh decade of life.

Since the study participants were healthy, the following exclusion criteria were taken into account in order to prevent any disorder-related artifacts occurrence as in [28]: any diagnosed knee disorders, post-traumatic syndromes, neurological disorders, functional limitations or pains.

All study participants gave their informed consent and the experiments were carried out in accordance with the Declaration of Helsinki, and approved by the Bioethics Committee of the Opole Medical Chamber in Opole, Poland, (No. 202 of 6th June 2013) for studies involving humans.

Signal acquisition and features

During experiments, which relied on the PFJ function of each knee assessment, an acceleration sensor was placed 1 [cm] above the patella apex and mounted with a double-sided adherent tape (see Fig. 1). The evaluation was based on test lasting 6 seconds only.

The procedure was the same as in [28]. The study participants were tested in sitting position and each of the below listed tasks was repeated 4 times:

- loose hanging legs with knees flexed at 90◦;
- full knee extension: 90−0◦;
- knee reflexion: 0−90◦.

Table 1. Study participants anthropometric characteristics.[1]Values are expressed by mean ± standard deviation

Parameters	Age (years)				
	(20-29)	(30-39)	(40-49)	(50-59)	60-69)
No. of subjects (M/F)	60(26/34)	56(24/32)	40(17/23)	31(13/18)	33(13/20)
Age (years)[1]	23.8±2.4	34.9±3.0	45.5±2.7	55.0±3.0	64.8±2.9
Body-mass (kg)[1]	69.3±11.8	71.5±14.0	73.5±12.1	74.6±11.5	72.9±9.0
Height (cm)[1]	170.4±7.5	169.3±8.5	168.5±8.9	167.0±6.7	164.2±8.2
BMI[1]	23.8±3.1	24.9±4.5	25.9±3.7	26.7±3.4	27.1±3.4

The constant velocities of flexion, extension motions and measuring conditions were kept at the level of 82 beats per minute and measured with a metronome. The knee joint angle was measured with an electrogoniometer placed on the knee lateral aspect with the rotation axis at the lateral femur condyle.

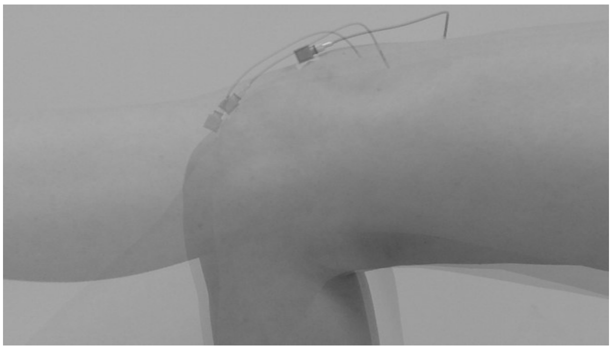

Fig. 1. Sample picture of the VAG recording protocol

The vibroarthrographic signals were recorded with a piezoelectric accelerometer (4513B-002, Bruel&Kjaer Sound and Vibration Measurement A/S, Denmark). The data was recorded in the periodicity between 0.7 and 1000 [Hz] at sampling frequency Fs = 10 [kHz] and filtered with a 4-th order zero-phase Butterworth band-pass digital filter with the cut-off frequencies at 50 and 1000 [Hz]. Authors of [17] used similar study protocol (4 leg swings in about 4 seconds), with 500 [Hz] sampling rate.

VAG signal features used in this research were divided into two groups: linear, including Variance of the Mean Squares (VMS, eq. 1), amplitude of the signal calculated as a difference between mean values of the four highest and the four lowest values (R4, eq. 2), and two frequency features (P1, eq. 3 and P2, eq. 4) [29, 30, 24, 22] and non-linear, including multi-scale entropy (MSE) [31] and recurrence rate (RR) [32, 33].
The VMS measure is defined as follows:

(1) $$VMS = \frac{1}{k}\sum_{i=1}^{k}(s_v(i) - \mu)^2,$$

where s_v is k-sample signal of 5 [ms] mean-squared VAG signal. High values of the VMS indicate a significant deterioration of the movement quality in the joint, associated with an increase in vibration.
Amplitude is defined as follows:

(2) $$\mathrm{R4} = \frac{1}{4}\sum max_4(s) - \frac{1}{4}\sum min_4(s) ,$$

where $s$is the VAG signal,min_4 and max_4 are the four smallest and greatest values of the s, respectively. High values of this parameter usually indicate repetitive high peaks in each cycle of movement, appearing to be typical of large macroscopic changes in cartilage, or dislocation/inconsistency of the joint surfaces.

Frequency parameters, P1 and P2 are defined in the following manner:

(3) $$\sum_{f=50[Hz]}^{250[Hz]} STFT\{s\}(t,f), \text{ and}$$

(4) $$\sum_{f=250[Hz]}^{450[Hz]} STFT\{s\}(t,f),$$

where $STFT\{s\}$is the Short Time Fourier Transform [34, 30, 35] of the VAG signal s, with the 150-sample Hanning window, with 100-sample overlap. High values of P1 and P2 are typical for increased kinetic friction, resulting from degenerative changes and are usually associated with microscopic changes in cartilage.

Recurrence Rate (RR) [32, 33] is a measure describing the Recurrence Plot, specifically the density of its recurrence points. Muliscale Sample Entropy (MSE) [31] is an extension of standard sample entropy [36] measure, quantifying signal fluctuations over a range of time scales. Low values of those complexity measures (both RR and MSE) may indicate deterioration of lubrication, irregularity, fibrosis and softening of the articular cartilage.

Results

In this study the authors focused on correlation between linear, such as VMS, R4, P1 and P2 and non-linear VAG parameters, such as, recurrence rate (RR) and multi-scale entropy (MSE). As stated above – the impaired joint motion quality can be considered a clinical sign for articular surfaces disorders [21], thus, the results presented in this work were applied for the purpose of knee articular surfaces assessment. As mentioned in the previous part of this work – the experimental group was similar to the one presented in: [28] and consisted of 220 healthy study participants divided into 5 age-related groups.

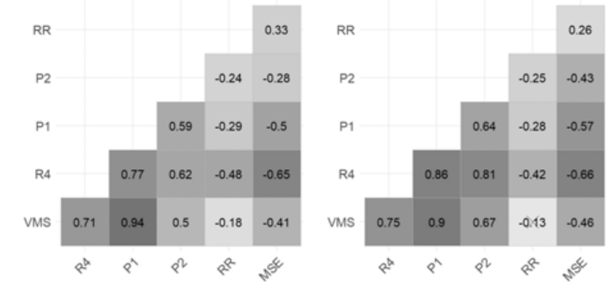

Fig. 2. Correlations between VAG parameters, differentiated by gender. Intensity of the grey color corresponds to the absolute value of the correlation

Figure 2 shows correlations between specific VAG features for female and male participants. Although some differences can be spotted, general correlations among both genders seem similar. The highest correlations can be observed between P1 and VMS and P1 and R4 pairs. VMS and R4 pair also seem correlated, which is not surprising, considering previously mentioned pairs. Second frequency parameter, i.e. P2 feature, shows lower correlation coefficient with P1, R4 and VMS.

Both non-linear features, i.e. RR and MSE, seem negatively correlated with linear parameters and positively, although not highly, between themselves. The highest negative correlation can be observed between the entropy and amplitude features.

Figure 3 shows dependence of VMS feature on the age of participant, for female and male participants. Positive correlation between age and VMS parameter can be observed. Note, however, that for both genders, there are more outliersin the older ages. Note also histograms for both genders; values seem to be mostly spread across lower values region, while higher points are occupied by few outliers.

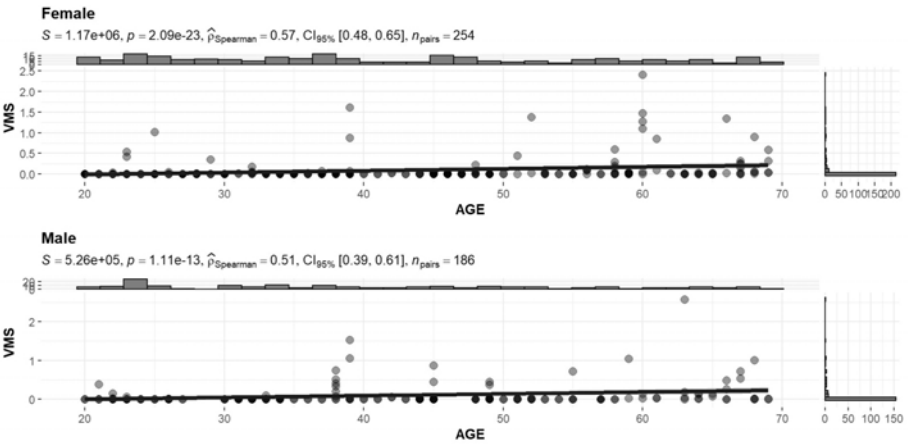

Fig. 3. Variance of the Mean Squares (VMS) feature as the function of age, differentiated by gender

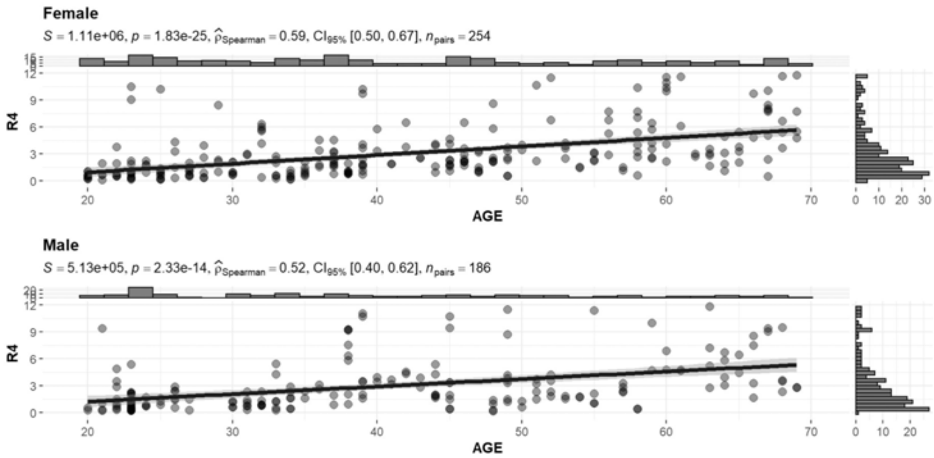

Fig. 4. . Amplitude feature (R4) as the function of age, differentiated by gender

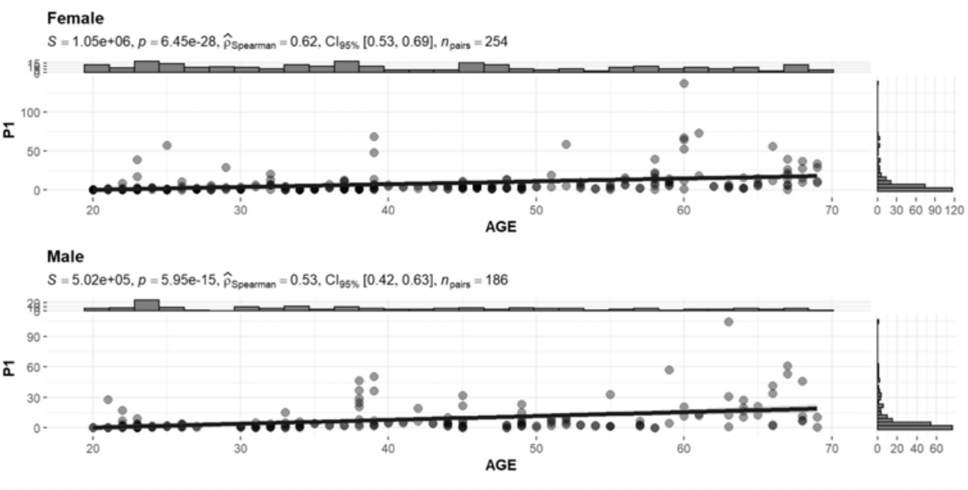

Fig. 5. P1 feature (50−250 [Hz]) as the function of age, differentiated by gender

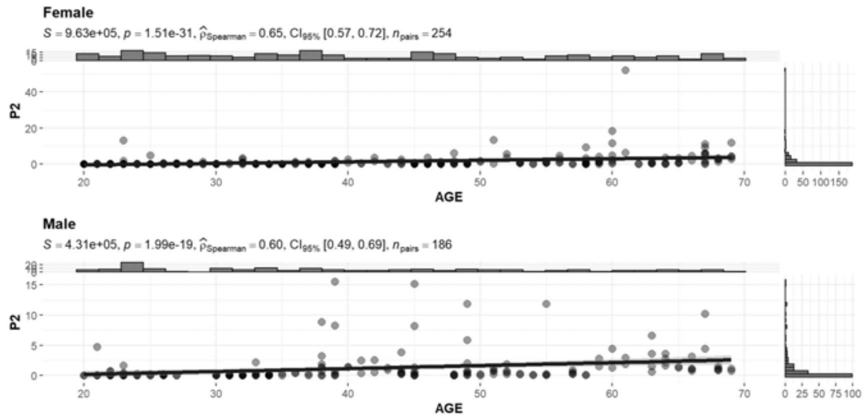

Fig. 6. P2 feature (250−450 [Hz]) as the function of age, differentiated by gender

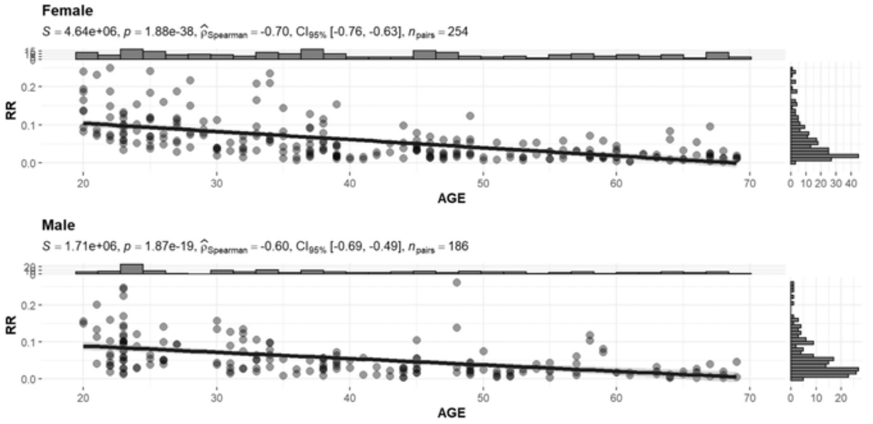

Fig. 7. Recurrence Rate feature as the function of age, differentiated by gender

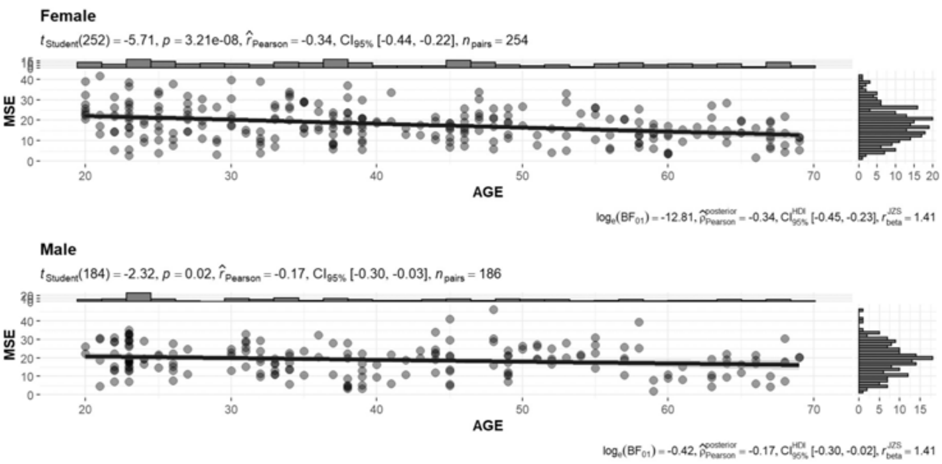

Fig. 8. Multi-scale entropy feature as the function of age, differentiated by gender

Similar to Figure 3, Figure 4 shows dependence of R4 feature on the age of participant, for female and male participants. Similarly, positive correlation between age and R4 feature is clearly visible. Unlike VMS, however, values of R4 are more uniformly spread.

Both P1 (Figure 5) and P2 (Figure 6) features demonstrate positive correlations with age. Similarly to VMS, their values seem to be more spread across whole values range and more outliers are visible in older ages. Interestingly, for both parameters, males seem to have more outliers, especially in older ages.

Also, it is worth noting that correlation between P1 and P2 (note Fig. 3) is positive, but rather low. It indicates that spectral fluctuations in 50−250 Hz and 250−450 Hz ranges slightly differ with their dependence on participant's age.

Non-linear features, i.e. recurrence rate, showed on Figure 7, and multi-scale entropy, showed on Figure 8 seem negatively correlated with age. Also, in both features, regression lines seem very similar between genders.

Discussion and Conclusions

As stated previously, correlations across parameters does not proved to be substantially different between genders. High correlations between VMS and R4 parameters may indicate that variance of the mean squared signal increases with the increase of amplitude, measured by R4 feature. Along with the information from Figures 3 and 4, it is clear, that vibroarthrograms recorded for participants of older age tend to be more fluctuating, in general. Previously mentioned outliers of the VMS values seem to bias regression line. However, both correlations between VMS and R4 and between R4 and age taken together, seem to confirm positive correlation between VMS and age.

Frequency parameters, i.e. P1 and P2, also turned out to be positively correlated with age, however, only moderately between themselves. It confirms previous research done on the VAG frequency analysis, where different frequency ranges provided different information about the signal [37].

Based on the obtained results the nonlinear measure of RR was the best in differentiating age groups, it showed no statistically significant differences only in the comparison of groups 40 − 49 with 50 − 59, all other comparisons were significant. The MSE gave the worst results. Comparing non-linear parameters to the linear – the P2 is similar to RR, where the other are worse (but still better than the MSE).

One of the main advantages of the non-linear parameters is that they give information about the dynamics of the signal.

In conclusion, we found that, in the context of age groups differentiation, VMS parameter is highly correlated with the amplitude of the vibroarthrogram. Moderate negative correlations have been found between linear and non-linear features. Recurrence Rate proved to be highly negatively correlated with the age of participant.

Specific parameters of the VAG signal seem to be sensitive enough for assessment of biomechanical changes within the knee joint. Therefore, vibroarthrography, as a computeraided decision support system, proved to be a helpful tool for clinicians. More research is needed that would focus on the extraction of VAG signal features for the differentiation of VAG signals in different contexts, including those from other joints. It appears that it is critical to concentrate on all components of this technique, including measuring equipment, analytic methodologies, and classification algorithm choices, while also simplifying the whole evaluation procedure. process of selecting such minimizer for an example CAD system. The stochastic optimizer will be compared to the deterministic one in terms of the simplicity, robustness, quality of the results and speed.

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