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APPLICATION OF ACOUSTIC SIGNAL PROCESSING METHODS IN DETECTING DIFFERENCES BETWEEN OPEN AND CLOSED KINEMATIC CHAIN MOVEMENT FOR THE KNEE JOINT

Abstract

The paper presents results of preliminary research of analysis of signals recorded for open and closed kinematic chain in one volunteer with chondromalacia in both knees. The preliminary research was conducted in order to establish the accuracy of the proposed method and will be used for formulating further research areas. The aim of the paper is to show how FFT, recurrence plots and recurrence quantification analysis (RQA) can help in bioacoustic signals analysis.

1. INTRODUCTION

We are living in the age of galloping technical progress. Computers are getting smaller and faster, communication is instantaneous and we are able to cure more and more diseases. Unfortunately, such a situation also leads to negative consequences (Maciejewski et al., 2014). We are spending more time sitting down and not performing any physical activities, and the average age in western population

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is increasing. Also, obesity is now a major factor. This results in the increased prevalence of cardiovascular conditions (Maciejewski, Dzierżak, Surtel & Saran, 2016; Maciejewski, Surtel & Dzida, 2015) and problems with joints and muscles. Especially the knee is a joint that can easily fail in an overweight patient, resulting in problems with everyday life.

Unfortunately, it is not easy to diagnose early symptoms of knee cartilage degeneration. Usual methods include ultrasonography, magnetic resonance and arthroscopy. In some cases, computer tomography can be performed. These methods generate significant costs and can sometimes provide inconclusive results. On the other hand, the procedure of arthroscopy is relatively cheap and can give precise information, but is an invasive procedure, and, as such, results in damage to some tissue. Due to these factors it is vitally important to develop and test a precise, cheap and simple procedure to assess the level of joint tissue degeneration. By early diagnosis it is possible to mitigate some consequences by introducing proper supplementation and physical therapy.

Therefore, the progress in the development of numerical methods related to the processing of acoustic signals used in medicine can make it possible to collect and analyze the necessary data without the need for costly or invasive tests on humans (Karpiński, Jaworski, Jonak & Krakowski, 2019).

Understanding and determining the nature of the test signal provides the basis for the considerations related strictly to data analysis. This is particularly important in the case of discovering new areas, where it is difficult to make both quantitative and qualitative analyzes, based only on the present state of knowledge. Therefore, it is necessary to illustrate the characteristics of the studied waveforms. The above concept is reflected in the preliminary studies on vibroacoustic processes recorded for the cartilage tissues of the knee joint.

Due to the individualized nature of muscular activity of people with degenerative changes of joints, including damaged joint relieving, it seems particularly important to take up the subject of recorded signals analysis for open and closed kinematic chain cases.

2. KNEE ACOUSTIC EMISSION

Knee joint is the biggest and most complex joint in the human body and one of the most susceptible to mechanical injuries and degenerative changes. This joint is a combination of three bones: the tibia, fibula, and femur. The joint includes a patella. The knee is the joint that transmits the loads that occur when moving between these elements. The major part taking the load in the knee joint is a thick layer of hyaline cartilage (6–7 mm), which under physiological conditions provides almost frictionless movement between the forming bones (Zubrzycki, Karpiński & Górniak, 2016; Karpiński et al., 2019). The occurrence of frequent excessive overloads, mechanical injuries and disturbances of lubricating properties of synovial fluid cause accelerated wear and degeneration of cartilage structures, which may result in deterioration of both quantitative and qualitative aspects of joint functioning (Krakowski et al., 2018).

Typical diagnostic imaging methods such as magnetic resonance imaging, ultrasonography or computed tomography usually generate high costs and limited availability especially for patients treated in smaller medical centers. In addition, in relation to cartilage structures, they are characterized by insufficient accuracy and diagnostic sensitivity. Therefore, it is extremely important to look for alternative methods to assess the degree of damage/degeneration of joint surfaces, for example, an assessment based on the generated vibroacoustic processes related to the change in the characteristics of the mechanical structures included in the joint (Kręcisz & Bączkowicz, 2018). The analysis of the generated vibroacoustic processes can provide the information about the tribological properties of the joint, the quantity and properties of the synovial fluid and the functioning of articular cartilage during movement which is omitted in classical imaging diagnostics (Bączkowicz, Kręcisz & Borysiuk, 2019; Kim, Seo, Kang & Song, 2009; Wiens, Prahalad & Inan, 2016).

Data presented in the following works (Bączkowicz et al., 2019; Choi, Ahn, Ryu, Nagao & Kim, 2018; Goodacre et al., 2018; Rangayyan, Oloumi, Wu & Cai, 2013; Shark, Chen & Goodacre, 2010, 2011) show that there is a strong relationship between the level f vibroacoustic emission and the degree of damage to the joint surfaces of the knee joint. It has been reported, that knee joints of patients with degenerative changes produce vibroacoustic emissions with higher frequency, higher peaks and longer duration compared to healthy knees. It is believed that the analysis of acoustic signals provides specific information about the tribological properties of the joint, related to, inter alia, the state of vitreous cartilage and / or rheological features of synovial fluid. Diagnostic methods based on generated vibroacoustic processes allow physicians to assess joint performance under normal operating conditions, with particular emphasis on its functions in motion. This allows for a significant extension of therapeutic activities such as the selection of exercises and pharmacological treatment. The analysis of vibroacoustic processes provides us with information on the quality of traffic and its dynamic parameters, which is a significant extension of imaging methods (Bączkowicz & Majorczyk, 2014).

Currently, there are no strict guidelines on how to measure vibroacoustic processes generated by the knee joint, or for the measuring system itself and the methods of processing recorded signals. Some authors suggest measurements in an open kinematic chain (Bączkowicz et al., 2019; Kim et al., 2009; Wu et al., 2016). The measurements are carried out in a sitting position for repetitive movements. The use of an open kinematic chain may play a particularly important role in cases of patients with advanced degenerative changes affecting the limitation of the range of motion in the joint. Some of the studies include tests in a closed kinematic chain, the range of motion will involve repeated sit – stand – sit movements (Shark et al., 2011; Wiens et al., 2016). From a biomechanical point of view, movements performed in a closed and open kinematic chain generate various patterns of muscle activity, thus changing the distribution of forces and moments acting on the elements of the knee (Adouni & Shirazi-Adl, 2009). The aim of the work is to compare the results of analyzes for the waveforms recorded in the open and closed kinematic chain using typical signal processing methods and recursive graphs.

3. SIGNAL ANALYSIS

Signal analysis in a broader sense can be performed in time domain, frequency domain or using an approach in between. Time analysis usually focuses on calculating signal power, average value, median, variance, autocorrelation or fitting an autoregressive model. Also, trend analysis is performed in time domain. Analysis in time domain is usually the first step during processing and can give some idea on the type and character of signal. Nevertheless, when audio signals, or, in broader sense, vibrations are involved, it is necessary to perform calculations in frequency domain. The most popular frequency analysis methods involve Fourier analysis and wavelet transform.

3.1. Fourier analysis

Fourier analysis is a well-tested and widely used signal processing method aimed at representing the signal as a sum of trigonometric functions, most frequently sine and cosine. It allows for fast bandwidth calculation, signal filtration by decomposition, thresholding of chosen parameters and synthesis, noise removal and generation of spectrograms. Due to the nature of signal processing begin done by means of digital computing Fast Fourier Transform, or FFT, is used frequently to reduce numerical complexity by a significant factor. The transform results in a series of numerical values corresponding to amplitudes of sine vibrations for different frequencies in the signal. This series represents the whole time period of the analyzed signal. Such an approach can often result in loss of information about short, rare artifacts in the signal due to averaging. To counter this problem the idea of Short Time Fourier Transform, or STFT. In this case FFT is performed in a time window shorter than the total length of signal. This can be done by continuous or discrete time STFT. In the first case the position of the time window, usually Hann or Gaussian, changes by one sample every time the calculation is performed, in the second case the signal is broken into chunks which usually overlap to reduce artifacts, and FFT is performed for each chunk. Continuous time STFT produces more data and is more time consuming, while discrete time STFT can result in some omissions, so a proper method should be chosen wisely.

3.2. Recurrent plots, recurrence quantification analysis

Recurrent plot (RP) is a technique nonlinear signal analysis at dynamical approaches (Litak, Gajewski, Syta & Jonak, 2008; Litak, Syta, Gajewski & Jonak, 2010; Litak, Syta & Rusinek, 2011; Syta, Jonak, Jedliński & Litak, 2012). It is a representation of the results in the form of the symmetric N x N matrix, shown by the points symbolizing the presence of recursion. RP are a kind of visualization of the repeatability of the states of the studied dynamic system, where a phase space trajectory visits at the same area in the phase space. According to Takens (Takens, 1981), the phase space trajectory can be reconstructed from a time series by the time delay embedding. Recurrence states in the phase space located at recurrence plot are signed as black dots. There are various possibilities of the character of the examined waveform. The appearance of diagonal lines on RP means states where analyzed parts of the phase trajectory run parallel. Other possibilities include existence of periodic recurrent structures specific to periodic and quasi-periodic systems. Research focused on recurrence plots provide a wide range of current structures analysis. By means of diagonal lines length histogram, certain measures relevant for recurrence quantification analysis are determined. The most popular of them are: recurrence rate (RR), determinism (DET), maximal diagonal line length (LMAX), trend (TREND), entropy (ENTR), laminarity (LAM) and trapping time (TT). Recurrence rate parameter informs about the density of the recurrence points in the entire recurrence plot, it measures the probability of the recurrence of a certain state. Determinism specifies the number of recursive points forming linear segments parallel to the main diagonal line of the diagram, the presence of them reveals that the analyzed phenomenon is deterministic. The LMAX parameter determines the length of the longest diagonal line. Measure called trend provides information about the non-stationarity of the studied process and about the existence of a linear or periodic trend of process changes. Shannon entropy (Shannon, 1948) (ENTR) is the measure of the complexity of the deterministic structure in the system. Its high value is specific to dynamic periodic behavior, low ENTR values corresponds to chaotic systems. Laminarity parameter corresponds to share of recurrent states. This measure shows stability of the system behavior, low LAM value could indicate intermittency. Finally, trapping time refers to the average length of vertical lines, it shows the time of the remaining in a specific state.

4. MATERIALS AND METHODS

The tests were performed on a 36 year old white causasian female with diagnosed chondromalacia in both knees with the pain being significantly greater in the right knee. The patient used to take part in intense physical activities between the age of 20 and 30. During the test session both knees were independently tested. Three cases were recorded per knee, including slow and fast knee straightening while seated (open kinematic chain) and slow bodyweight squats (closed kinematic chain). The measurement system is presented below.

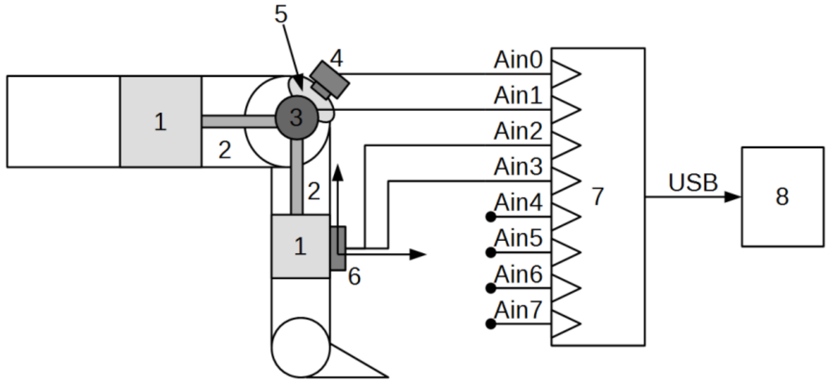

Fig. 1. Measurement system: 1 – elastic sleeve with Velcro regulation, 2 – rigid struts for attachment of the rotary encoder 3, 4 – solid body microphone placed on the skin directly touching the kneecap 5, 6 – inertial measurement unit for position estimation, 7 – analogue interface card for signal acquisition, 8 – computer used for data recording

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 equated to about 76 microvolts resolution. The position of the microphone was chosen after knee palpation during movement to maximize the amplitude of vibrations. Signals recorded from the left knee are shown on the figure below.

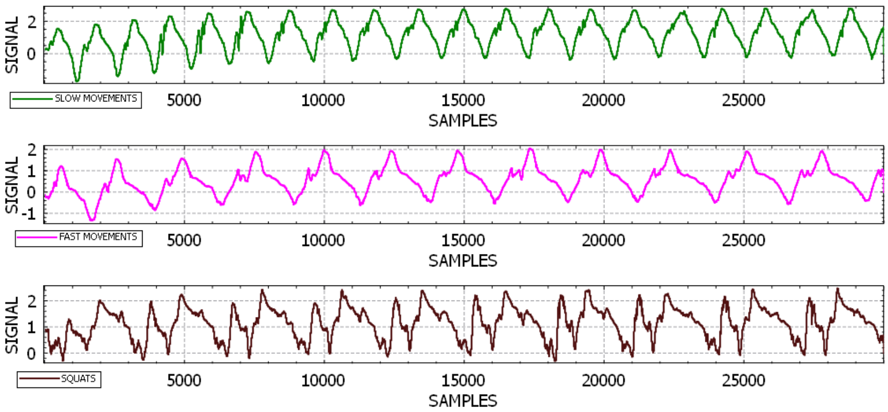

Fig. 2. Acoustic signals recorded from the left knee

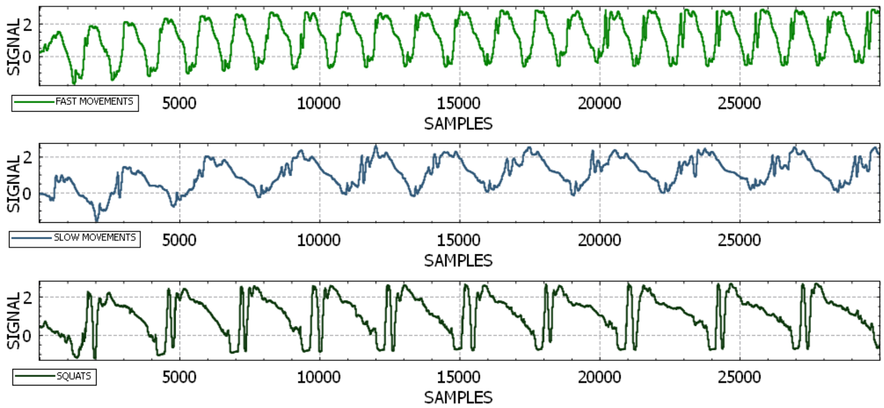

Fig. 3. Acoustic signals recorded from the right knee

5. RESULTS

The results were obtained using Matlab software and recurrence plot and recurrence quantification analysis toolbox (Chen & Yang, 2012; Yang, 2011; *Tool box of recurrence plot and recurrence quantification analysis – File Exchange – MATLAB Central*, n.d.). Fourier analysis was performed using Fast Fourier Transform with timebase of 1 kHz and the spectrum was limited from 0.2 to 6 Hz. In all the spectrum plots the basic frequency of knee movements is visible as the main peak. The spectrums show greater levels of higher order components for the right knee, especially in the closed kinematic chain during squats. This correlates with higher level of creaking of the right knee due to the tissue degeneration.

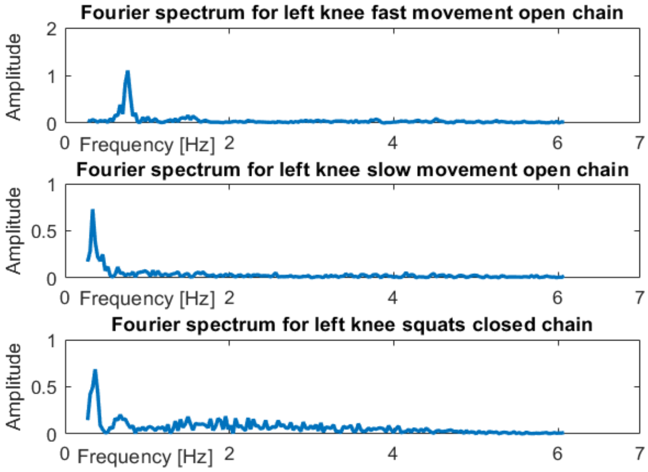

Fig. 4. Spectrums of signal acquired during left knee movement

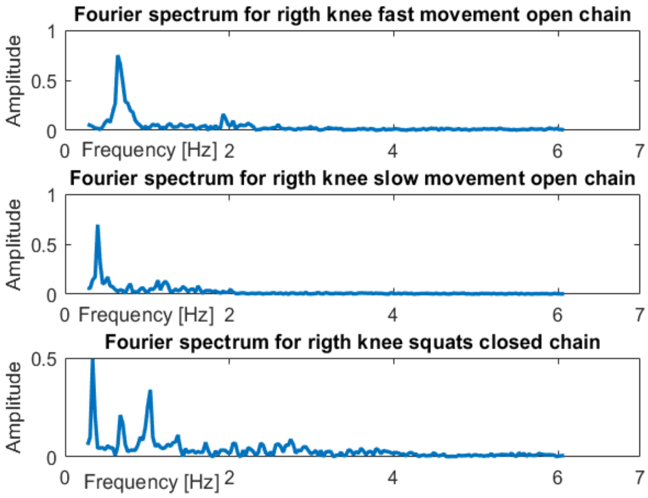

Fig. 5. Spectrums of signal acquired during left knee movement

Figure 4 shows left leg movements during the straightening (opened kinematic chain) and bodyweight squats movement – closed kinematic chain. Respectively, for right limb straightening movements and bodyweight squats movements FFT plots were visualized by figure 5. Recurrence plots presented on figure 6 are connected with left leg straightening movement (opened kinematic chain). Figure 7 shows recurrence plot of bodyweight squats movement for left limb. Figure 8 visualizes recurrent plots of opened kinematic chain movement for right leg. Recurrence plot of closed kinematic movement for right limb was presented on figure 9.

a) b)

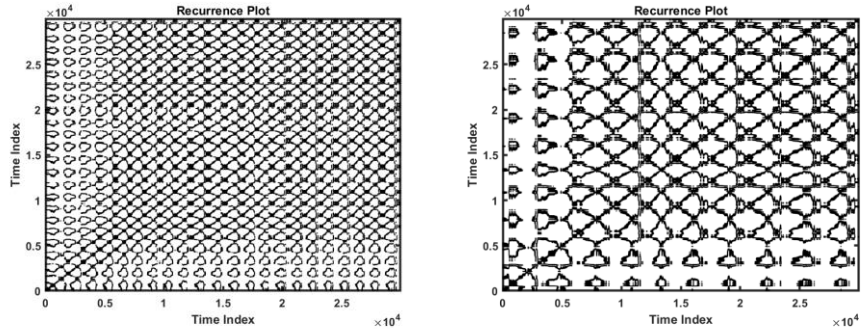

Fig. 6. Recurrence plots of left limb straightening movement in opened kinematic chain: a) fast movement, b) slow movement

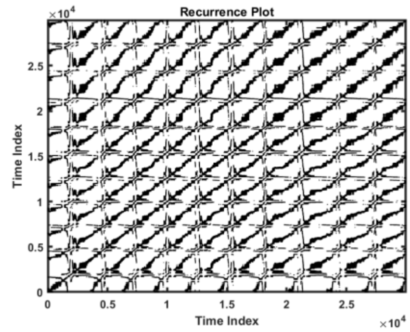

Fig. 7. Recurrence plot of left limb bodyweight squat movement in closed kinematic chain

a) b)

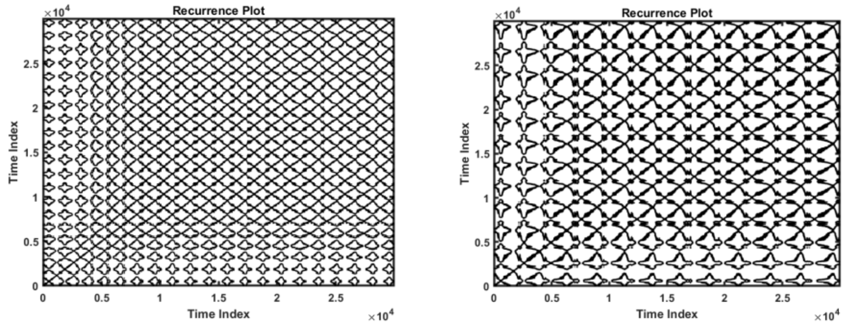

Fig. 8. Recurrence plots of right limb straightening movement in opened kinematic chain: a) fast movement, b) slow movement

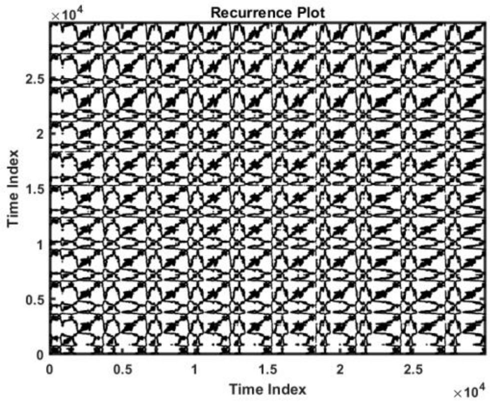

Fig. 9. Recurrence plot of left limb bodyweight squat movement in closed kinematic chain

Recurrence plots analysis shows a clear tendency to fading to the upper left and lower right corners in the case of acoustic signal registered for movement in open kinematic chain. Such feature could indicate nonstationarity or drift/trend component containing (Marwan, Carmenromano, Thiel & Kurths, 2007). In studied case of lower limb movements in opened and closed kinematic chains this phenomenon is related to the presence of initial muscle tension (closed kinematic chain) and lack of initial muscle tension for movement in opened kinematic chain. Structures visible on plots suggest that the signals have quasi-periodic character.

Results of conducted recurrence quantification analysis were placed in Tab.1.

Tab. 1. Recurrence quantification analysis

Type	RR	DET	LMAX	ENTR	TREND	LAM	TT
LFO	16.297	99.288	29983	6.639	-3.725e-18	99.564	53.266
LSO	22.600	99.791	29983	7.343	-1.770e-17	99.866	95.405
LSC	18.403	99.354	14682	7.068	-2.125e-18	99.623	90.181
RFO	19.032	99.565	29982	6.671	9.178e-18	99.738	60.001
RSO	31.054	99.775	29983	7.805	-4.100e-18	99.873	140.654
RSC	29.747	99.503	27413	7.050	2.657e-18	99.706	79.640

where: LFO – left knee fast movement in opened kinematic chain, LSO – left knee slow movement in opened kinematic chain, LSC – left knee bodyweight squat movement (close kinematic chain), RFO – right knee fast movement in opened kinematic chain, RSO – right knee slow movement in opened kinematic chain, RSC – right knee bodyweight squat movement (close kinematic chain)

Trapping time fast movement in opened kinematic chain: on right limb TT is more than on left one by 12%, in case of slow movement it is respectively 47%. Above relationship does not occur in closed kinematic chain. For bodyweight squatting movement it was obtained inverse relationship: TT on left limb is more than on right one by 13%. Recurrent rate parameter describes repeatability of states degree. Carried out RQA analysis showed higher RR values for slow movements. LMAX measure has provided information related to registered data character. Lower values of this parameter were observed for movements in closed kinematic chain. It could indicate an increased degree of chaos in the investigated process. DET, LAM, ENTR and TREND values constitute the confirmation of recorded data periodic character.

6. CONCLUSION

The FFT data shows significant levels of higher order components in the signal during right knee movement in closed kinematic chain, which also corresponded to the greatest level of discomfort for the patient. It may be suggested, that it is connected to degradation of cartilage tissue in the knee area. It is impossible to provide hard evidence to support this claim, as more data needs to be collected and processed. Nevertheless, the results look promising.

From the kinematic chain type standpoint of RQA, the trapping time parameter is important. Longer TT for the opened kinematic chain movement could point to necessity of movement time extending due to the pain occurrence. The reverse dependency appearance (squatting movement in closed kinematic chain) confirms the increased discomfort for the examined limb existence. Squat is a type of highly individualized movement where differences are observed on the background of the anatomy, varying mobility degrees or finally the tissue damage size and pain. Therefore, the patient may shorten the time of passing through the given range during the squat movement (the angle of the limb position), where the greatest discomfort appears (Brinckmann, Hoefert & Jongen, 1981; Gilsanz et al., 1994; Marras, Jorgensen, Granata & Wiand, 2001).

REFERENCES

Adouni, M., & Shirazi-Adl, A. (2009). Knee joint biomechanics in closed-kinetic-chain exercises. *Computer Methods in Biomechanics and Biomedical Engineering*, *12*(6), 661–670. doi:10.1080/10255840902828375

Bączkowicz, D., Kręcisz, K., & Borysiuk, Z. (2019). Analysis of patellofemoral arthrokinematic motion quality in open and closed kinetic chains using vibroarthrography. *BMC Musculoskeletal Disorders*, *20*(1). doi:10.1186/s12891-019-2429-z

Bączkowicz, D., & Majorczyk, E. (2014). Joint motion quality in vibroacoustic signal analysis for patients with patellofemoral joint disorders. *BMC Musculoskeletal Disorders*, *15*, 426. doi:10.1186/1471-2474-15-426

Brinckmann, P., Hoefert, H., & Jongen, H. T. (1981). Sex differences in the skeletal geometry of the human pelvis and hip joint. *Journal of Biomechanics*, *14*(6), 427–430. doi:10.1016/0021-9290(81)90060-9

Chen, Y., & Yang, H. (2012). Multiscale recurrence analysis of long-term nonlinear and nonstationary time series. *Chaos, Solitons & Fractals*, *45*(7), 978–987. doi:10.1016/j.chaos.2012.03.013

Choi, D., Ahn, S., Ryu, J., Nagao, M., & Kim, Y. (2018). Knee Acoustic Emission Characteristics of the Healthy and the Patients with Osteoarthritis Using Piezoelectric Sensor. *Sensors and Materials*, *30*(8), 1629. doi:10.18494/SAM.2018.1877

Gilsanz, V., Boechat, M. I., Gilsanz, R., Loro, M. L., Roe, T. F., & Goodman, W. G. (1994). Gender differences in vertebral sizes in adults: biomechanical implications. *Radiology*, *190*(3), 678–682. doi:10.1148/radiology.190.3.8115610

Goodacre, J., Schlueter, D. K., Shark, L.-K., Spain, L., Platt, N., Platt, N., Mercer, J., Waterton, J. C., Bowes, M., Dixon, M., & Huddleston, J. (2018). Identifying Novel Acoustic Emission Biomarkers for Use in Knee Osteoarthritis Clinical Trials. *Rheumatology*, *57*(suppl_3), key075.321. doi:10.1093/rheumatology/key075.321

Karpiński, R., Jaworski, Ł., Jonak, J., & Krakowski, P. (2019). Stress distribution in the knee joint in relation to tibiofemoral angle using the finite element method. *MATEC Web of Conferences*, *252*, 07007. doi:10.1051/matecconf/201925207007

Kim, K. S., Seo, J. H., Kang, J. U., & Song, C. G. (2009). An enhanced algorithm for knee joint sound classification using feature extraction based on time-frequency analysis. *Computer Methods and Programs in Biomedicine*, *94*(2), 198–206. doi:10.1016/j.cmpb.2008.12.012

Krakowski, P., Gerkowicz, A., Pietrzak, A., Krasowska, D., Jurkiewicz, A., Gorzelak, M., & Schwartz, R. A. (2018). Psoriatic arthritis – new perspectives. *Archives of Medical Science*. https://doi.org/10.5114/aoms.2018.77725

Kręcisz, K., & Bączkowicz, D. (2018). Analysis and multiclass classification of pathological knee joints using vibroarthrographic signals. *Computer Methods and Programs in Biomedicine*, *154*, 37–44. doi:10.1016/j.cmpb.2017.10.027

Litak, G., Gajewski, J., Syta, A., & Jonak, J. (2008). Quantitative estimation of the tool wear effects in a ripping head by recurrence plots. *Journal of Theoretical and Applied Mechanics*, *46*(3), 521–530.

Litak, G., Syta, A., Gajewski, J., & Jonak, J. (2010). Detecting and identifying non-stationary courses in the ripping head power consumption by recurrence plots. *Meccanica*, *45*(4), 603–608. doi:10.1007/s11012-009-9265-4

Litak, G., Syta, A., & Rusinek, R. (2011). Dynamical changes during composite milling: recurrence and multiscale entropy analysis. *The International Journal of Advanced Manufacturing Technology*, *56*(5), 445–453. doi:10.1007/s00170-011-3195-8

Maciejewski, M., Dzierżak, R., Surtel, W., & Saran, T. (2016). Human ECG indicators for fast screening and evaluation. In R. S. Romaniuk (Ed.) (1003131). Presented at the Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments, Wilga, Poland. doi:10.1117/12.2249149

Maciejewski, M., Surtel, W., & Dzida, G. (2015). Human ECG signal parameters estimation during controlled physical activity. In R. S. Romaniuk (Ed.) (96621P). Presented at the XXXVI Symposium on Photonics Applications in Astronomy, Communications, Industry, and High-Energy Physics Experiments, Wilga, Poland. doi:10.1117/12.2205811

Maciejewski, M., Surtel, W., Wójcik, W., Masiak, J., Dzida, G., & Horoch, A. (2014). Telemedical systems for home monitoring of patients with chronic conditions in rural environment. *Annals of Agricultural and Environmental Medicine*, *21*(1), 167–173.

Marras, W. S., Jorgensen, M. J., Granata, K. P., & Wiand, B. (2001). Female and male trunk geometry: size and prediction of the spine loading trunk muscles derived from MRI. *Clinical Biomechanics*, *16*(1), 38–46. doi:10.1016/S0268-0033(00)00046-2

Marwan, N., Carmenromano, M., Thiel, M., & Kurths, J. (2007). Recurrence plots for the analysis of complex systems. *Physics Reports*, *438*(5–6), 237–329. doi:10.1016/j.physrep.2006.11.001

Rangayyan, R. M., Oloumi, F., Wu, Y., & Cai, S. (2013). Fractal analysis of knee-joint vibroarthrographic signals via power spectral analysis. *Biomedical Signal Processing and Control*, *8*(1), 23–29. doi:10.1016/j.bspc.2012.05.004

Shannon, C. E. (1948). A Mathematical Theory of Communication. Reprinted with corrections from *The Bell System Technical Journal*, *27*, 379–423, 623–656.

Shark, L.-K., Chen, H., & Goodacre, J. (2010). Knee Acoustic Emission: A Clue to Joint Ageing and Failure. *Rheumatology*, *49*, I79–I79.

Shark, L.-K., Chen, H., & Goodacre, J. (2011). Knee acoustic emission: A potential biomarker for quantitative assessment of joint ageing and degeneration. *Medical Engineering & Physics*, *33*(5), 534–545. doi:10.1016/j.medengphy.2010.12.009

Syta, A., Jonak, J., Jedliński, Ł., & Litak, G. (2012). Failure Diagnosis of a Gear Box by Recurrences. *Journal of Vibration and Acoustics*, *134*(4), 041006. doi:10.1115/1.4005846

Takens, F. (1981). Detecting strange attractors in turbulence. In D. Rand & L.-S. Young (Eds.), *Dynamical Systems and Turbulence, Warwick 1980* (898, pp. 366–381). Berlin, Heidelberg: Springer. doi:10.1007/BFb0091924

Tool box of recurrence plot and recurrence quantification analysis – File Exchange – MATLAB Central. (2019, March 13). Retrieved from https://www.mathworks.com/matlabcentral/fileexchange/58246-tool-box-of-recurrence-plot-and-recurrence-quantification-analysis

Wiens, A. D., Prahalad, S., & Inan, O. T. (2016). VibroCV: A computer vision-based vibroarthrography platform with possible application to Juvenile idiopathic arthritis. *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)* (pp. 4431–4434). IEEE. https://doi.org/10.1109/EMBC.2016.7591710

Wu, Y., Chen, P., Luo, X., Huang, H., Liao, L., Yao, Y., Wu, M., & Rangayyan, R. M. (2016). Quantification of knee vibroarthrographic signal irregularity associated with patellofemoral joint cartilage pathology based on entropy and envelope amplitude measures. *Computer Methods and Programs in Biomedicine*, *130*, 1–12. doi:10.1016/j.cmpb.2016.03.021

Yang, H. (2011). Multiscale Recurrence Quantification Analysis of Spatial Cardiac Vectorcardiogram Signals. *IEEE Transactions on Biomedical Engineering*, *58*(2), 339–347. doi:10.1109/TBME.2010.2063704

Zubrzycki, J., Karpiński, R., & Górniak, B. (2016). Computer aided design and structural analysis of the endoprosthesis of the knee joint. *Applied Computer Science*, *12*(2), 84–95.