http://doi.org/10.35784/iapgos.6139

received: 24.04.2024 | revised: 23.05.2024 | accepted: 25.05.2024 | available online: 30.06.2024

CONCEPT AND VALIDATION OF A SYSTEM FOR RECORDING VIBROACOUSTIC SIGNALS OF THE KNEE JOINT

Robert Karpiński [1], Anna Machrowska[1], Marcin Maciejewski[2], Józef Jonak[1], Przemysław Krakowski[3,4]

[1]Lublin University of Technology, Department of Machine Design and Mechatronics, Lublin, Poland, [2]Lublin University of Technology, Department of Electronics and Information Technology, Lublin, Poland, [3]Medical University of Lublin, Department of Trauma Surgery and Emergency Medicine, Lublin, Poland, [4]Carolina Medical Center, Orthopaedic and Sports Traumatology Department, Warsaw, Poland

Abstract. *Cartilage degeneration is a serious health condition in modern society, leading to problems in mobility and significant reduction in the quality of life of patients of all ages. It is mainly caused by obesity, workload, sports or trauma to the joint. Proper diagnosis is crucial to implement appropriate treatment to stop the further degeneration of the tissue. Usually the assessment is performed by using magnetic resonance. This paper describes the design and application of an alternative measurement system for vibroartography of the knee joint. The use of such device allows for fast, safe, easy and cheap assessment of joint condition, which in turn can lead to proper treatment planning. Similar portable systems can be rapidly deployed and used by entry level medical staff in hospitals, clinics or at patient's home. The system consists of an orthosis, set of three vibroacoustic sensors, encoder for reading knee position, microcontroller with galvanic barrier and battery power and a computer for data storage and processing. The system is light, simple and portable. Data is recorded in both closed and open kinematic chains. Results show over 90% diagnostic accuracy based on the data obtained in the process of testing this device. In the future, the system will be further miniaturized and completely placed on the orthosis, leading to more portability and diagnostic merit.*

Keywords: vibroarthtography, knee, osteoarthritis, articular cartilage, sensors, acoustic signals

KONCEPCJA I WALIDACJA UKŁADU DO REJESTRACJI SYGNAŁÓW WIBROAKUSTYCZNYCH STAWU KOLANOWEGO

Streszczenie. *Zwyrodnienie chrząstki jest poważnym schorzeniem współczesnego społeczeństwa, prowadzącym do problemów w poruszaniu się i znacznego obniżenia jakości życia pacjentów w każdym wieku. Jest to spowodowane głównie otyłością, obciążeniami, sportem lub urazami stawu. Właściwa diagnoza jest kluczowa dla wdrożenia odpowiedniego leczenia, które zapobiegnie dalszej degeneracji tkanki. Zwykle ocenę przeprowadza się za pomocą rezonansu magnetycznego. W artykule opisano konstrukcję i zastosowanie alternatywnego systemu pomiarowego do wibroartografii stawu kolanowego. Aplikacja takiego urządzenia pozwala na szybką, bezpieczną, łatwą i tanią ocenę stanu stawu, co z kolei może pomóc w zaplanowaniu odpowiedniego leczenia. Podobne systemy mobilne można szybko wdrożyć, ponieważ mogą być używane przez podstawowy personel medyczny w szpitalach, klinikach lub w domu pacjenta. System składa się z ortezy, zestawu trzech czujników wibroakustycznych, enkodera do odczytu pozycji stawu kolanowego, mikrokontrolera z barierą galwaniczną i zasilaniem bateryjnym oraz komputera do akwizycji, archiwizacji i przetwarzania danych. System jest lekki, prosty i przenośny. Dane są rejestrowane zarówno w zamkniętych, jak i otwartych łańcuchach kinematycznych. Wyniki wykazują ponad 90% trafności diagnostycznej na podstawie danych uzyskanych w procesie testowania tego urządzenia. W przyszłości system będzie jeszcze bardziej zminiaturyzowany i całkowicie umieszczony na ortezie, co zapewni większą przenośność i wartość diagnostyczną.*

Słowa kluczowe: wibroartografia, staw kolanowy, choroba zwyrodnieniowa stawów, chrząstka stawowa, czujniki, sygnały akustyczne

Introduction

Cartilage is one of the most important tissues of synovial joints. Due to its specialized structure it provides smooth and painless joint motion. This organized structure and most importantly lack of nerve endings and vessels with combination of sparse number of chondrocytes grossly decreases cartilage healing potential [6, 9]. Once injured, the ongoing process of cartilage degeneration begins, leading to inevitable osteoarthritis (OA) development [13, 22]. OA is one of the leading causes of disability around the globe with over 527 million individuals affected [26, 32]. In past years, OA was mainly considered as a disease affecting elderly. However, newer papers show that cartilage lesions are one of the most commonly found intraarticular injuries which can also be found in younger population [20]. Multiple factors such as obesity, workload, sports, trauma or inflammatory diseases can accelerate cartilage degradation process [4, 33, 35, 36]. With progression of OA pain, restricted range of motion and stiffness occur, which impede daily activities including work and leisure. Multiple treatment options have been proposed in literature and in clinical setting, however, none of the joint sparing techniques can't fully restore hyaline cartilage. Gold standard for treatment of end stage disease is total joint replacement [15, 39]. This surgery, in majority of cases, reduces pain and increases range of motion, however, every joint replacement surgery requires a revision surgery after some time due to joint implant wear after prolonged use. In case of total knee replacement (TKR) reoperation rate after 15 years reaches 81–92% [5, 34]. Therefore orthopaedic community seeks ways to postpone necessity for TKR, especially in younger population. Joint sparing techniques can prolong the time before reoperation, however, they need to be implemented at early stage of the disease. In clinical setting accurate diagnosis is the most important factor in proper treatment. Conventional X-ray is still considered as a gold standard for diagnosing OA and treatment planning. However, conventional radiography only shows bone changes in regard to OA development and scoring systems are based on changes that are visible after the point where joint sparing treatment can be introduced [17]. Therefore, conventional radiography has very limited utility in early OA diagnostics. For diagnosis of early cartilage changes, magnetic resonance imaging (MRI) is still considered as a gold standard [21, 23]. However, this is a costly examination which requires specialized equipment and skilled medical professionals to conduct and evaluate the findings. Moreover, faith in radiological findings in clinical setting brings to a situation where up to 20% of patients referred for knee MRI did not receive previous proper physical examination, especially when general practitioners were obliged to perform examination [38]. This situation prolongs the waiting list for patients, that require MRI examination, which in turn consumes human resources. Moreover, MRI was shown to grossly underestimate cartilage lesion grade [20] and in some intraarticular lesions physical examination showed higher sensitivity than MRI [21, 23, 24] Given that orthopaedic society seeks diagnostic modality, which would be cheap, reproducible, easy and fast to perform even in general practitioners office. Vibroarthrography (VAG) seems to fulfill these requirements. Vibroacoustic diagnosis of the knee joint, also known as vibroacoustic signal analysis (Vibroarthrography, VAG) or acoustic emission, uses specialized sensors to record the sounds and vibrations generated by joint motion. This data is then analyzed to identify potential abnormalities or tissue damage [16]. This diagnostic modality is based on change of vibrations generated by joint surfaces during motion. Changes in mechanical and tribological properties can be recorded during joint motion [40]. This signals can be evaluated as a potential diagnostic modality for noninvasive, simple and fast cartilage examination [30, 31]. First mention in literature considering potential usage of VAG as a diagnostic method reaches back to 1902 [3], however since then not much development has been achieved in regard to utilization of this diagnostic method. In recent years, some papers concerning newer acquisition and classification methods have been published [10, 14, 28], which showed high diagnostic accuracy [11, 12]. Nevertheless, there is still no consensus on signal acquisition and classification methods. Despite many years of research into the development of vibroacoustic joint diagnostics, no consensus has been reached on the measurement system, methods for processing non-linear and non-stationary VAG signals, and classification methods to effectively assess damage to knee joint structures. However, despite the existence of general guidelines and standard procedures in some research and diagnostic protocols, the detailed parameters of the systems presented to date have varied significantly depending on the study objectives, available technology and investigator preferences. Therefore, it is essential that each study or clinical application be thoroughly documented, including equipment specifications and testing procedures, to enable comparability of results and further advances in the field. In this study we present our proposed method of signal processing and acquisition with validation of our measuring system. Further development and standardization of vibroacoustic diagnostic procedures for the knee joint may contribute to a better understanding of the mechanisms of damage to the joint, thereby improving diagnosis, monitoring of disease progression and treatment effectiveness.

1. Concept and construction of the measurement system

The device was designed to satisfy the following requirements:

- ability to acquire low-frequency vibration signals originating from knee joint during standing up from the sitting position and squatting;
- ability to measure the angle of the joint for motion reference during the exercise;
- at least 10 bits of precision and 1kHz sampling frequency;
- inclusion of a galvanic separator and battery power for patient safety;
- simple data format for easy transfer and further processing;
- robustness and resistance to mistreatment during data acquisition in realistic hospital conditions;
- three microphones mounted on top of and on the sides of the knee joint.

The differences in knee joint biomechanics during exercises in open and closed kinetic chains are crucial for understanding their impact on rehabilitation and training, and in this case, diagnostics. The measurement system for recording acoustic signals has been designed to enable the recording of signals in various sequences of movements that include exercises in both open and closed kinetic chains.Simplified system schematic is presented in figure 1.

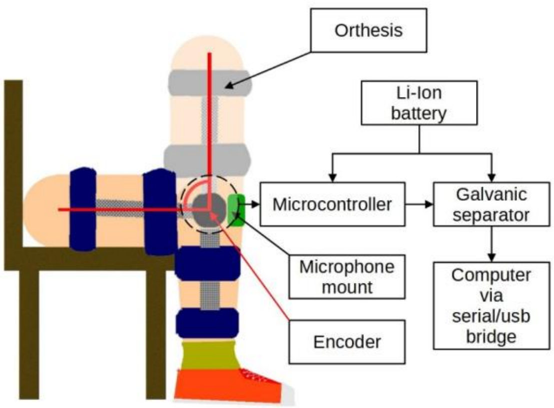

Fig. 1. Simplified system schematic

1.1. Mechanical structure

Reliable and repeatable angle measurement required use of a stabilised scaffolding in the form of a knee orthosis. For this purpose T Scope® Premier Post-Op Knee Brace was chosen It is a tool used in post – surgery rehabilitation and features four soft straps with patient compliant padding, telescoping rails for length adjustment, joint with angle range control and quick release locks. The padding is constructed of soft, biocompatible, breathable materials to both increase patient comfort and provide robust mounting points to the metal rails on left and right side of the joint. The device can be used with both left and right leg [41]. The device can operate as a scaffold for lateral knee stabilisation and angular motion limitation in cases, when extreme joint positions can cause damage and interfere with the healing process. The orthosis can be used as a tool to stabilise the knee and limit pain in arthritis and similar conditions.

1.2. Mechanical structure

Proper vibration acquisition required the use of proper microphone with included sufficient acoustic coupling. Due to thick subcutaneous tissue in the knee area it is impossible to use normal, acoustic microphones designed to work in atmospheric conditions. Multiple machine vibration sensor solutions exist, but most of them are either very heavy, require stable reference bases or permanent placement on the measured surface. For this application it was necessary to choose a small, lightweight, robust and self – contained measurement solution. These requirements were satisfied by CM-01B [7], a device produced by TE Connectivity. It uses sensitive piezoelectric PVDF foil coupled with low noise preamplifier Overall mechanical dimensions are presented in figure 2.

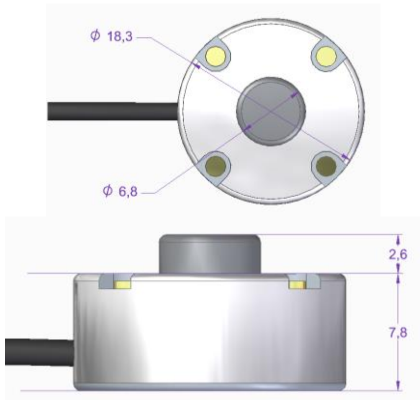

Fig. 2. Mechanical dimensions of CM-01B microphone

This device weighs at only about 20 grams and offers a bandwidth between 8 Hz and 2.2 kHz, small form factor, high sensitivity of 40 V/mm (Fig. 3) and significant impact and water resistance, which is crucial in practical hospital applications. The device accepts from 4.5 to 30 V and draws 100 µA current. Due to its construction it minimizes external noise (Fig. 4) and can be securely mounted. This device is perfect for use in medical applications. Three mounting plates were 3d printed out of thermoplastic polyurethane rubber and secured using medical – grade tape to the skin on the patient's knees.

Angle measurement was done using a digital magnetic rotary encoder EMS22A50-D28-LT6 from Bourns (Fig. 5). The encoder offers 10 bits of resolution and operates on 3.3 and 5 V, drawing 20 mA maximum current. During operation the device's mechanism can withstand 10,000 rpm and still offer accuracy no less than 1.4° in the worst case. The device communicates via SSI interface, which allows for quick and easy implementation in the software of the main microcontroller. It's constructed of high – quality materials and is resistant to water, low temperatures and mechanical damage.

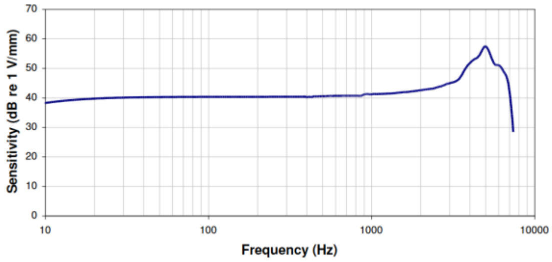

Fig. 3. Frequency characteristics of the microphones

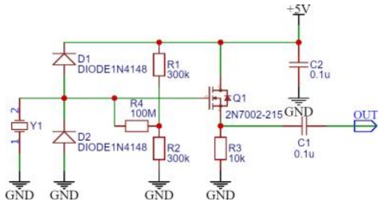

Fig. 4. Internal structure of the microphone and amplifier circuit

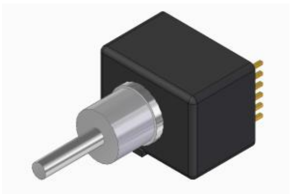

Fig. 5. Rotary encoder used in the device

To minimize the risk to the patient and increase resistance to noise it was necessary to implement means of galvanic isolation. For this purpose adum4160 module was used [1]. This device operates from 3.1 to 5.5 V and is USB2.0 compliant, offering bidirectional speeds up to 12 Mbps. The ESD performance is compliant to ANSI/ESD STM5.1-2007 standard, and the device itself is immune to up to 25 kV/µs transients. The overall module footprint and internal structure are presented below (Fig. 6).

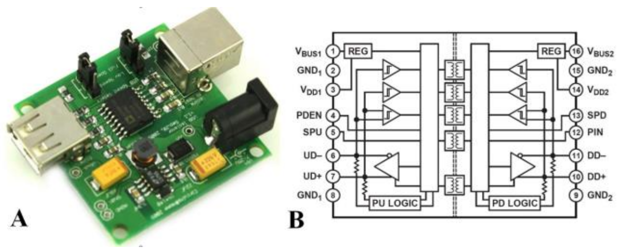

Fig. 6. Separator module

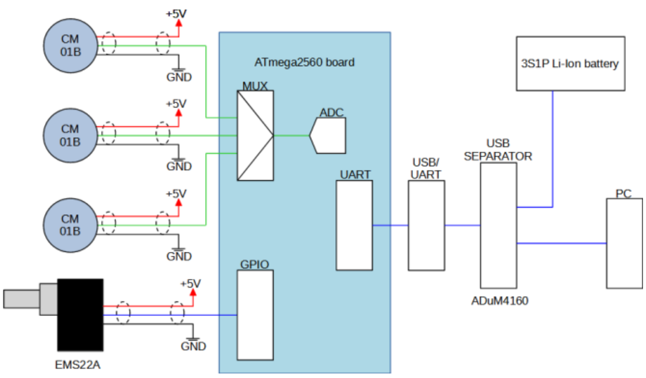

Fig. 7. Internal schematic of the system

Analog to digital conversion and initial data manipulation was done using AtMega2560 microcontroller in the form of Arduino Mega board. The microcontroller was programmed using the Arduino environment in C++. The resolution of the analog to digital conversion was 10 bits. Coupled with the microphones sensitivity it provided sensitivity to skin movements as small as 0.02 µm/s. The overall system schematic and sensor placement are presented in the figures 7 and 8.

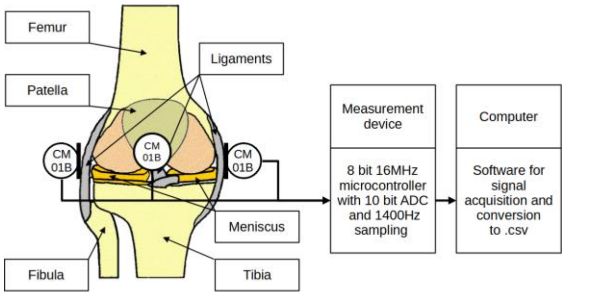

Fig. 8. Sensor placement and signal measurement

The casing of the electronical section of the system was 3d printed out of polylactic acid (PLA) using a standard FDM printer. The photo of the completed device is presented in figure 9. Example waveforms recorded with the created measurement system for a healthy and sick person, as well as the filtering process are shown in Fig. 10.

Fig. 9. The complete device

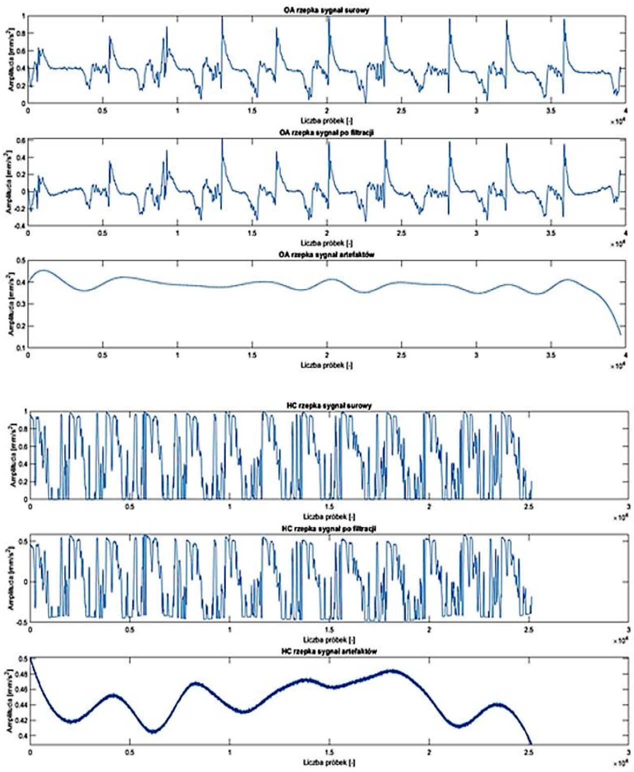

Fig. 10. Example signals recorded for a healthy (left) person and one with confirmed degenerative changes (right)

1.3. Software

The main control software was created in C++. The control loop consists of subsequent sensor reads triggered by an internal 1400Hz interrupt clock. The readings are then formatted in ASCII and sent via the serial/usb converter to the main computer, where the data is read and saved using RealTerm application. Data format consists of a stream of comma separated values and flow control/synchronisation data. This way it is possible to retain consistent data flow, while still making the file easy to read and process. Data then undergoes preprocessing, including linear approximation of any missing values, and is ready to be used later.

2. Discussion

Vibroacoustic diagnostics of knee joints is a modern, non-invasive method for assessing the condition of knee joints, based on the analysis of acoustic or vibrational signals generated by joint structures during movement. It is cheaper and faster than traditional imaging methods, such as MRI or CT, making it potentially widely available in various clinical settings. However, due to the lack of detailed guidelines regarding the process of recording, processing, and classifying vibroacoustic signals, it is not commonly used in clinical conditions. This method is particularly useful in the diagnosis and monitoring of the progress of treatment for chronic joint disorders and in rehabilitation. Its main limitation, however, is its lesser ability to provide detailed structural images, which can affect diagnostic precision compared to more advanced imaging techniques. In our study we have proposed and validated both the diagnostic device as well as examination protocol. Our previous studies have shown diagnostic accuracy surpassing 90% [11,12,13]. Other researchers also showed sensitivity for cartilage lesions surpassing 90% [19]. Nevertheless, at this moment our proposed system was only able to distinguish injured cartilage from healthy ones. Even though, our accuracy is relatively high and corresponds to other authors, the most important question in clinical setting is with which grade cartilage lesion we are dealing, and at this time there is very limited number of papers concerning grading [25]. Kręcisz et. al showed that for patellofemoral joint specificity for cartilage grading can be reach 69% in the patello-femoral joint [25]. However, this study as a reference point used MRI images, which seems to be a bias to the results as MRI was shown to grossly underestimate the cartilage lesion grade [20]. Nevertheless this study shows that there is potential in VAG for not only distinguishing between healthy and injured cartilage but also for grading system based on VAG. Kim et al showed that VAG can be also an viable option for detection of other intraarticular injuries such as meniscal tears [18]. In literature there is no consensus concerning sensor location and examination protocol. Andersen et al showed that sensor location and knee movement protocol influences the results [2]. Therefore, it is necessary for further development of standardized protocols for clinical examination and sensor locations. Some clinical utility of VAG have been shown in 2018 in a pilot study performed on adolescents with juvenile idiopathic arthritis [37]. In their study they have shown on small group of patients that after treatment VAG algorithm classified individuals as healthy. This study shows a great potential for monitoring progress of disease and future use of proposed system. With many questions concerning signal processing and acquisition to be answered VAG has shown to be possible diagnostic tool in future. Our proposed method of cartilage evaluation at this time does not classify the cartilage lesion grade but fulfills requirements necessary for screening purposes. It is quick, safe, cheap and reproducible, moreover if in future combined with application it will not require skilled and experienced medical staff to conduct an examination. However, at this stage of development our proposed examination system requires greater study and control group. Also what is worth noting is the fact, that mostly commercially based equipment was used in developing the system. With ease of component access the examination setup is easy to reproduce in different world regions with minimal costs. Moreover, ease of use and building the system opens up an opportunity to utilize the system as a screening method in large populations such as military or police force to pick up prone individuals with risk of OA development in the service. We hope that in future, greater patient group and more advanced signal processing methods will enable full VAG cartilage evaluation.

Machine learning methods and neural networks, which allow for the identification of non-obvious patterns and are used in cases requiring a nonlinear approach, can support and supplement the proposed measurement system. Neural networks are effectively applied in solving nonlinear classification problems in technical sciences and medicine [8]. In engineering, they analyze material patterns, predict failures, and optimize production processes, thereby reducing the number of experiments and lowering the costs of experimental research [27, 29]. In medicine, they are used for medical image analysis, patient health monitoring, and treatment outcome prediction, and find applications in vibroacoustic diagnostics of joints. Challenges associated with these applications include the interpretability of models and ethical issues. The development of these technologies promises further advances in various fields where nonlinear methods are necessary.

3. Conclusions

The results obtained demonstrate that the proposed solution facilitates the effective registration of vibroacoustic signals in a simple and repeatable manner. The acoustic signals obtained using the proposed measurement system, when subjected to appropriate filtering and processing, constitute a valuable source of diagnostic information that allows for cost-effective and non-invasive diagnostics of knee joint structure damage. Vibroacoustic diagnostics of knee joints may serve as an alternative to the significantly more expensive imaging diagnostics methods currently in use.

Although vibroacoustic joint diagnostics offers promising benefits such as lower cost, speed and non-invasiveness, its role as an alternative to traditional imaging still needs further research and development. It is particularly promising in applications where the cost and availability of traditional imaging are limitations (MRI, CT). To fully evaluate its potential, further research will be needed to improve its accuracy and integrate it more widely into medical practice.

In the future the device will be rebuilt using STM32 platform and miniaturized by including an SD card for data storage, integrated li-ion battery and compact PCB with integrated LCD screen for debugging and data acquisition control. The miniaturized device will then be small enough to be placed on the orthosis, which will remove the need for long, cumbersome cables and make the device application much easier.

References

[1] ADUM4160 Datasheet and Product Info | Analog Devices [https://www.analog.com/en/products/adum4160.html].

[2] Andersen R.E., Arendt-Nielsen L., Madeleine P.: Knee joint vibroarthrography of asymptomatic subjects during loaded flexion-extension movements. Med Biol Eng Comput. 56(12), 2018, 2301–2312.

[3] Blodgett W.E.: Auscultation of the Knee Joint. The Boston Medical and Surgical Journal. 146(3), 1902, 63–66.

[4] Cameron K. et al.: Incidence of Physician-Diagnosed Osteoarthritis Among Active Duty United States Military Service Members. Arthritis & Rheumatology 63(10), 2011, 2974–2982.

[5] Castagnini F. et al.: Total Knee Replacement in Young Patients: Survival and Causes of Revision in a Registry Population. The Journal of Arthroplasty 32(11), 2017, 3368–3372.

[6] Cibere J. et al.: Natural history of cartilage damage and osteoarthritis progression on magnetic resonance imaging in a population-based cohort with knee pain. Osteoarthritis and Cartilage 19(6), 2011, 683–688.

[7] Contact microphone CM-01B, Technical Data Sheet. 2015.

[8] Falkowicz K., Kulisz M.: Prediction of Buckling Behaviour of Composite Plate Element Using Artificial Neural Networks. Adv Sci Technol Res J. 18(1), 2024, 231–243.

[9] Goldring M.B.: Update on the biology of the chondrocyte and new approaches to treating cartilage diseases. Best Practice & Research Clinical Rheumatology 20(5), 2006,1003–1025.

[10] Jonak J. et al.: A preliminary study on the use of EEMD-RQA algorithms in the detection of degenerative changes in knee joints. IOP Conf Ser: Mater Sci Eng. 710(1), 2019, 012037.
[11] Karpiński R. et al.: Diagnostics of Articular Cartilage Damage Based on Generated Acoustic Signals Using ANN – Part I: Femoral-Tibial Joint. Sensors 22(6), 2022, 2176.
[12] Karpiński R. et al.: Diagnostics of Articular Cartilage Damage Based on Generated Acoustic Signals Using ANN – Part II: Patellofemoral Joint. Sensors 22(10), 2022, 3765.
[13] Karpiński R. et al.: Comparison of selected classification methods based on machine learning as a diagnostic tool for knee joint cartilage damage based on generated vibroacoustic processes. Appl Comput Sci. 19(4), 2023, 136–150.
[14] Karpiński R., Machrowska A., Maciejewski M.: Application of acoustic signal processing methods in detecting differences between open and closed kinematic chain movement for the knee joint. Applied Computer Science 15(1), 2019, 36–48.
[15] Karpiński R. et al.: Evaluation of the Effect of Selected Physiological Fluid Contaminants on the Mechanical Properties of Selected Medium-Viscosity PMMA Bone Cements. Materials 15(6), 2022, 2197.
[16] Karpiński R.: Knee joint osteoarthritis diagnosis based on selected acoustic signal discriminants using machine learning. Applied Computer Science 18(2), 2022, 71–85.
[17] Kellgren J.H., Lawrence J.S.: Radiological assessment of osteo-arthrosis. Ann Rheum Dis. 16(4), 1957, 494–502.
[18] Kim K. S., Seo J. H., Song C. G.: An Acoustical Evaluation of Knee Sound for Non-invasive Screening and Early Detection of Articular Pathology. J Med Syst. 36(2), 2012, 715–722.
[19] Kiselev J. et al.: Detection of osteoarthritis using acoustic emission analysis. Medical Engineering & Physics 65, 2019, 57–60.
[20] Krakowski P. et al.: Knee MRI Underestimates the Grade of Cartilage Lesions. Applied Sciences 11(4), 2021, 1552.
[21] Krakowski P. et al.: Evaluation of diagnostic accuracy of physical examination and MRI for ligament and meniscus injuries. J Phys: Conf Ser. 1736, 2021, 012027.
[22] Krakowski P. et al.: Short-Term Effects of Arthroscopic Microfracturation of Knee Chondral Defects in Osteoarthritis. Applied Sciences 10(23), 2020, 8312.
[23] Krakowski P. et al.: Evaluation of the diagnostic accuracy of MRI in detection of knee cartilage lesions using Receiver Operating Characteristic curves. J Phys: Conf Ser. 1736, 2021, 012028.
[24] Krakowski P. et al.: Comparison of Diagnostic Accuracy of Physical Examination and MRI in the Most Common Knee Injuries. Applied Sciences 9(19), 2019, 4102.
[25] Kręcisz K., Bączkowicz D.: Analysis and multiclass classification of pathological knee joints using vibroarthrographic signals. Computer Methods and Programs in Biomedicine 154, 2018, 37–44.
[26] Long H. et al.: Prevalence Trends of Site-Specific Osteoarthritis From 1990 to 2019: Findings From the Global Burden of Disease Study 2019. Arthritis & Rheumatology 74(7), 2022, 1172–1183.
[27] Machrowska A. et al: Numerical prediction of the component-ratio-dependent compressive strength of bone cement. Applied Computer Science 16(3), 2020, 87–101.
[28] Machrowska A. et al.: Diagnostic factors for opened and closed kinematic chain of vibroarthrography signals. Applied Computer Science 15(3), 2019, 34–44.
[29] Machrowska A. et al.: Use of Deep Learning Networks and Statistical Modeling to Predict Changes in Mechanical Parameters of Contaminated Bone Cements. Materials 13(23), 2020, 5419.
[30] Nevalainen M. T. et al.: Acoustic emissions and kinematic instability of the osteoarthritic knee joint: comparison with radiographic findings. Sci Rep. 11(1), 2021, 19558.
[31] Prior J. et al.: Analysis of high frequency acoustic emission signals as a new approach for assessing knee osteoarthritis. Annals of the Rheumatic Diseases 69(5), 2010, 929–930.
[32] Quicke J. G. et al.: Osteoarthritis year in review 2021: epidemiology & therapy. Osteoarthritis and Cartilage 30(2), 2022, 196–206.
[33] Reyes C. et al.: Socio-economic status and the risk of developing hand, hip or knee osteoarthritis: a region-wide ecological study. Osteoarthritis and Cartilage 23(8), 2015, 1323–1329.
[34] Roberts V. I., Esler C. N. A., Harper W. M.: A 15-year follow-up study of 4606 primary total knee replacements. Journal of Bone and Joint Surgery – British Volume 89-B(11), 2007, 1452–1456.
[35] Roemer F. et al.: Increased risk for radiographic osteoarthritis features in young active athletes: a cross-sectional matched case–control study. Osteoarthritis and Cartilage 23(2), 2015, 239–243.
[36] Schouten J. et al.: An update on the relationship between occupational factors and osteoarthritis of the hip and knee. Current Opinion in Rheumatology 14(2), 2002, 89–92.
[37] Semiz B. et al.: Using Knee Acoustical Emissions for Sensing Joint Health in Patients With Juvenile Idiopathic Arthritis: A Pilot Study. IEEE Sensors J. 18(22), 2018, 9128–9136.
[38] Solivetti F. M. et al.: Appropriateness of knee MRI prescriptions: clinical, economic and technical issues. La radiologia medica 121(4), 2016, 315–322.
[39] Szabelski J. et al.: Analysis of the Effect of Component Ratio Imbalances on Selected Mechanical Properties of Seasoned, Medium Viscosity Bone Cements. Materials 15(16), 2022, 5577.
[40] Van den Borne M. P. J. et al.: International Cartilage Repair Society (ICRS and Oswestry macroscopic cartilage evaluation scores validated for use in Autologous Chondrocyte Implantation (ACI) and microfracture. Osteoarthritis and Cartilage 15(12), 2007, 1397–1402.
[41] Zegarowa orteza stawu kolanowego BREG – komfort i stabilizacja (T-scope Knee) – Sklep Orteo.pl [https://www.orteo.pl/zegarowa-orteza-stawu-kolanowego-breg-komfort-i-stabilizacja-t-scope-knee] (cited 2023 Jul 8).

Ph.D. Eng. Robert Karpinski
e-mail: r.karpinski@pollub.pl

Completed his engineering and master's degrees at and then his doctoral studies at Lublin University of Technology. He is employed at the Faculty of Mechanical Engineering at Lublin University of Technology and the Faculty of Medicine at the Medical University of Lublin.
His professional work includes biomedical and mechanical engineering, biomechanics, biomaterials, application of numerical methods in mechanical engineering, biomedical signal processing, vibroacoustic diagnostics of machines, computer-aided design and 3D printing.

https://orcid.org/0000-0003-4063-8503

M.Sc., Eng. Anna Machrowska
e-mail: a.machrowska@pollub.pl

Holds the position of assistant at the Department of Fundamentals of Machine Design and Mechatronics at the Faculty of Mechanical Engineering of the Lublin University of Technology.
Her scientific interests primarily include signal processing methods, issues related to vibroacoustic diagnostics of machines, neural networks, and the construction of expert systems.

https://orcid.org/0000-0003-3289-2421

Ph.D. Eng. Marcin Maciejewski
e-mail: m.maciejewski@pollub.pl

Graduated first from Warsaw University of Technology as an engineer, and later from Lublin University of Technology as Ph.D. Eng. He works at the Lublin University of Technology, Faculty of Electrical Engineering and Computer Science. Experienced in designing and prototyping analog and digital devices for medical signal acquisition.
His professional work includes computer science, biomedical signal processing, robotics, electronics, computer aided design and 3d printing.

https://orcid.org/0000-0001-9116-5481

Prof. Józef Jonak
e-mail:j.jonak@pollub.pl

Head of the Department Machine Design and Mechatronics at Faculty of Mechanical Engineering, Lublin University of Technology.
His professional interests include digital signal processing, vibroacoustic diagnostics of machinery and aerospace propulsion systems, application of artificial intelligence in medical diagnostics, numerical analysis using the finite element method, design of mechatronic devices and drives.

https://orcid.org/0000-0003-4658-4569

M.D., Ph.D. Przemysław Krakowski
e-mail: przemyslaw.krakowski84@gmail.com

Graduated from Medical University of Lublin. Since 2020 academic teacher at Chair and Department of Traumatology and Emergency Medicine. Author or co-author of over 30 scientific papers published in peer reviewed journals. Since 2023 head of Science Department in Carolina Medical Center. In clinical practice deals with treatment of trauma and joint. diseases.

https://orcid.org/0000-0001-7137-7145