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

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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 examination is performed by using magnetic resonance. This paper describes the design and application of an alternative measurement system for vibroarthrography 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: vibroarthrography, knee, osteoarthritis, articular cartilage, sensors, acoustic signals.

KONCEPCJA I WALIDACJA UKŁADU DO REJESTRACJI SYGNAŁÓW WIBROAKUSTYCZNYCH STAWU KOLANOWEGO

Streszczenie. Zwyrodnienie chrząsztki 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 specjalista ośrodkowy za pomocą techniki magnetycznej. W artykule opisano konstrukcję i zastosowanie alternatywnego układu pomiarowego do wibroartrografi stawu kolanowego. Aplikacja takiego urządzenia pozwala na szybkie, bezpieczne, łatwe i niewielką ocenę stanu stawu, co z kolei może pomóc w zaplanowaniu odpowiedniego leczenia. Podobne systemy mobilne można używać w klinikach, szpitalach, klinicach ortopedycznych lub domu pacjenta. System składa się z ortozy, zestawu trzech czujników wibroakustycznych, encydora do odczytu pozycji stawu kolanowego, mikrokontrolera z bariernym galwanicznym i zasilaniem bateryjnym oraz komputera do odsyłania sygnałów. System jest lekkim, prostym i przestojowym. 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 łatwiejszy do zastosowania w praktyce.

Słowa kluczowe: wibroarthrografia, staw kolanowy, 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) replacement 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 replacement, 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, 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 signal 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 1 kHz 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.

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.

This device weighs at 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.
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).

The casing of the electronic 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.
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]. Kręczysz 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 good 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


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