Enhancing Vibroarthrography by using Sensor Fusion

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Abstract: Natural and artificial joints of a human body are emitting vibration and sound during the movement. The sound and vibration pattern of a joint is characteristic and changes due to damage, uneven tread wear, injuries, or other influences. Hence, the vibration and sound analysis enables an estimation of the joint condition. This kind of analysis, vibroarthrography (VAG), allows the analysis of diseases like arthritis or osteoporosis and might determine trauma, inflammation, or misalignment. The classification of the vibration and sound data is very challenging and needs a comprehensive annotated data base. Current existing data bases are very limited and insufficient for deep learning or artificial intelligent approaches. In this paper, we describe a new concept of the design of a vibroarthrography system using a sensor network. We discuss the possible improvements and we give an outlook for the future work and application fields of VAG.

1 INTRODUCTION

A joint is the connection between bones in the body, which link the skeletal system into a functional whole. They are constructed to allow for different degrees and types of movement (Kim et al., 2009). Joint disorder and diseases have a huge impact on the life of people and are the main cause for disability of elderly people. Disorders and diseases such as arthritis causing huge economic costs for nations. In the US, the costs for treating arthritis were $303.5 billion or 1% of the 2013 US Gross Domestic Product (GDP). One of the most common disease of joints is osteoarthritis (OA), a degenerative disease where changes in bones, articular cartilages and soft tissues occur. OA affecting nearly 10% of the population worldwide and is frequently observed in elderly people (44% in people ¿ 80 years). OA was the second most costly health condition treated at US hospitals in 2013. In that year, OA accounted for $16.5 billion, or 4.3%, of the combined costs for all hospitalizations (Murphy et al., 2017). Tools and technologies for quantify the health status of human joints outside of the clinical setting are investigated by researchers throughout the past decade include the analysis of vibration caused by human joints, the range of motion and gait analysis. The analysis of vibration is called Vibroarthrography (VAG) (McCoy et al., 1987) or Vibration arthrometry (Kernohan et al., 1990). VAG is a non-invasive screening tool for vibration and sound analysis of natural joints which was first introduced by McCoy et al. in 1985 (McCoy et al., 1987) (see Figure 1). The origin concept is older and referred to Carl Hueter in 1883 (Hueter, 1883).

2 MOTIVATION

Because of the demographic development, joint diseases are an increasing problem. Within the lifetime, approx. 90 % of the population will suffer on serious knee or hip problems, hereby women are more affected than men. In Germany, the most surgery is knee joint operation by more than 150,000 times per year. But often, a knee replacement is not needed and an artificial knee joint wound last forever. More than 60 % of joints that had to be replaced are younger than 7 years. Therefore, an easy to use measurement system is necessary. The usage of a sensor network that combines also the capability to measure mobility, strength, sound, weight, acceleration, and light reflection of the veins enables the assessment of a comprehensive representation of the joint and body condition. A measurement over time provides the determi-

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nation of a trend and allows a prognosis beside the diagnosis. To achieve this goal, the concept and design of a sensor system is necessary.

3 RELATED WORK

3.1 Sensor Selection

The analysis of knee joint sound experience a long history of investigation since 1976. Chu et al. published a series of papers investigating the acoustic pattern of knee joints. The researchers found that cartilage damage around the knee may be classified with acoustic sensors (Chu et al., 1978). Further they found, that pattern recognition in acoustic signals may be used to distinguish between normal, rheumatoid and degenerative knees (Chu et al., 1976). Later in 1985, a research team evaluated the diagnostic potential of vibration arthrography by examining 250 subjects who were undergoing diagnostic arthroscopy and suggested that VAG will become a significant diagnostic aid in the clinical evaluation of the locomotive system. In 86% of these cases, a characteristic signal was obtained. Further, it was possible to identify the affected side and determine how far posteriorly the mensical injury lay (Kernohan et al., 1986).

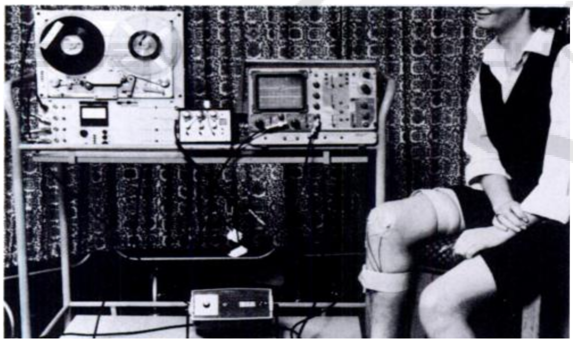


Figure 1: Subject attached to the recordings apparatus of VAG (McCoy et al., 1987).

Acceleration sensors show the advantage against microphones that microphones are sensing ambient noise from the environment too much and provide a limited frequency response in the audible range (Frank et al., 1990). Technologically, the acceleration of the skin is a mechanical wave. Hence, microphones are sensing airwaves that are generated by swinging material. The advantage of microphones is that they are able to detect higher frequencies and that no direct contact to the body is necessary. In relation to industrial inspections for mechanical machine components of wear by vibration analysis (Tandon and Choudhury, 1999; Orhan et al., 2006), the vibration and sound analysis of natural and artificial joints seems also to be manageable.

Recently, Klemm et al. studied the effects of sensor placement in their recent study and suggest, that mechanical extensions to the sensors, like 3D-printed caps may improve the data acquisition process. This ensures a amplification and a good transmission of lower frequency sounds (up to 125Hz) without attenuation of higher bands. During measurement, the sensors, off-the-shelf airborne audio sensors (SPH0645LM4H-B), were attached to the medial and lateral side of the knee. The measurement protocol consists of 20 sit to stand movements cycles (Klemm et al., 2019).

3.2 Feature Assessments

Several authors carried out research to investigate acoustic emission to assessing the dynamic integrity of joints (Prior et al., 2010). To detect acoustic emission, it is necessary to attach piezoelectric transducers to the surface of a structure under load. Shark et al. developed a joint angle based acoustic emission system. After the data acquisition process, the authors applied feature extraction techniques and dimensionality reduction to discriminate between healthy and unhealthy knees (Shark et al., 2010). Shark et al. found that the OA knees produce consistently and substantially more acoustic emission events with higher peak and mean magnitude than healthy knees.

Teague et al. used piezoelectric transducer, electret amd MEMS microphone, and IMU to assess the click location of knees during movement. During their study the researchers evaluated different types of microphone and carried out a comparison between on skin ad off skin joint sound signals. Further, they found that acoustic events occur at consistent joint angles during repetitive motions of healthy subjects. They suggest that joint sound measurements are repeatable with sensing technology that can be implemented in an inexpensive and wearable form factor (Teague et al., 2016). In 2018, Andersen et al. examined the methodical aspects of VAG assessment by investigating sensor placement and flexion-extension movements under load. Their study showed, that VAG parameters are affected by load level, movement type and the location of the accelerometer over the knee joint in asymptomatic subjects (Andersen et al., 2018).

3.3 Classification Techniques for VAG

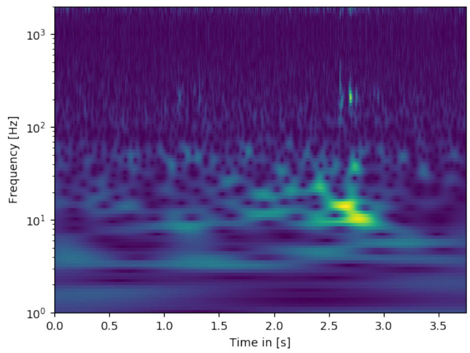
The current research in Vibroarthrography underlie different problems. Most research in vibroarthrography focus on the classification process (Rangayyan et al., 1997; Wu and Krishnan, 2011; Tai et al., 2015; Nalband et al., 2016), not considering different methods to acquire the data. It is not clear, which sensors (IMU, MEMS-microphone, piezoelectric transducer, Ultrasound) should be used to assess the current health state. Further, only little research is done evaluating the optimal sensor placement and environmental setting during the measurement. Several studies showed, that crepitus of the knee is dependent on the angular velocity (Kernohan et al., 1990) and the load affecting the knee joint during movement(Andersen et al., 2018). The usage of multiple sensors is needed due to the fact, that different states of pathology are found in different frequency bands (Frank et al., 1990) and may enable the early prevention of certain diseases. Peat et al. suggest that the American College of Rheumatology (ACR) clinical criteria to classify osteoarthritis seem to reflect later signs in advanced disease. They suspect that other approaches may be needed to identify early, mild osteoarthritis in the general population (Peat et al., 2006). The gold standard for diagnosing certain joint disorder is still X-ray or MRI . Those techniques are either radiating or expensive, rendering the constant monitoring impossible and not useful for early prevention. Abbot et al. concluded that the intense variability within signals is caused by contacting joint surfaces and forces during motion. This produce an understandable scepticism in the clinical community as to the reliability of vibration arthrometry and therefore making an adaption in medicine hard to accomplish (Abbott and Cole, 2013). The performance and capabilities of Vibroarthrography in detection of knee disorders are slight behind those of MRI/MRT. McCauly et al. reported 86% sensitivity and 74% specificity in detection of chondromalacia patellae using MRI (McCauley et al., 1992). Pihlajamaki et al. reported 83% sensitivity and 84% specificity for MRI images for stage III chondromalacia (Pihlajamäki et al., 2010).

3.4 Mobile VAG Systems

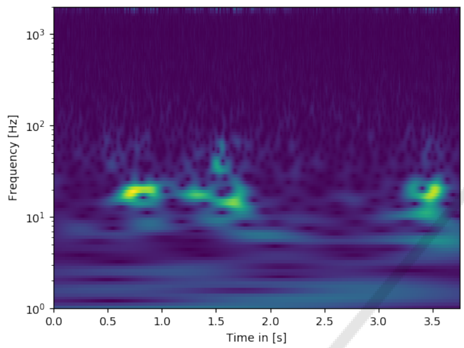
The need for constant monitoring of health status is not a new concept, considering the newest technologies in the Internet of Things area. Several devices such as smartwatches and fitness tracker measuring heart rate, respiration rate or general activity of human beings since a decade. The concept of constant monitoring of the knee health status, on the other hand, was first introduced a by a research group in 2016. Töreyin et al. (Toreyin et al., 2016) provided a prototype and framework to measure the sound made by joints during daily activities such as sit to stand transitions, walking or others. Another approach proposed by Msayib et al. in (Msayib et al., 2017) developed an intelligent monitoring system to measure the rehabilitation of total knee arthroplasty patients by assessing the range of motion of the knee. A recently proposed framework by Athavale and Krishan in (Athavale and Krishnan, 2019) is especially designed for the IoT era. By encoding the signals, the researchers enabling a efficient way for a constant monitoring of the condition of knee joint with vibroarthrography (or actigraphy). Unfortunately, Athavale and Krishan did not propose a effective sensor alignment to measure the knee joint sounds and vibrations. This work try to outline a concept based on the aforementioned research.

3.5 Challenges in VAG Systems

Although several researches reported high accuracy, sensitivity and specificity (¿95%) in classification of pathological knees via VAG (Kim et al., 2009; Nalband et al., 2017; Rangayyan et al., 2013), those results were obtained on a fairly dated dataset, consisting of 38 abnormal and 51 normal VAG signals obtained from a single axis accelerometer. Scalograms of abnormal and normal VAG signals are depicted in Figure 2. Rangayyan et al. suspect in (Rangayyan et al., 2013) that those remarkable results are obtained by overfitting on a specific dataset, regardless of the leave-one-out validation method used. This overfitting on an collected dataset may apply for other research in VAG as well. The acceptance of VAG in medicine is still far behind the established methods in this field (Shieh et al., 2016). Reasons might be the lack of resolution, the measurement principle, and that the sensor attachment on the skin varies by each individual. Further, the signal transportation is influenced by various parameters. This indicates that further research is needed, e.g. optimal sensor placement (Ota et al., 2016), number and type of sensors (Klemm et al., 2019), weight load during examination (Andersen et al., 2018) or state of the art feature extraction and classification techniques. Even today, a realistic recognition rate of certain joint diseases like knee, hip or hand osteoarthritis is not sufficient to obtain a precise result (Altman et al., 1986). Therefore, we need an enhanced VAG assessment and analysis system as follows.



(a) Scalogram of VAG signal without pathology



(b) Scalogram of VAG signal with pathology

Figure 2: VAG signal comparison.

4 ENHANCED CONCEPT OF THE VAG SYSTEM

As we worked out in the related work section, the existing concept of the assessment of a VAG Sensing System is insufficient. Therefore, we designed a concept that is more advanced, fuses heterogeneous sensors, and compensate the lacks and deficiencies of the existing VAG procedure.

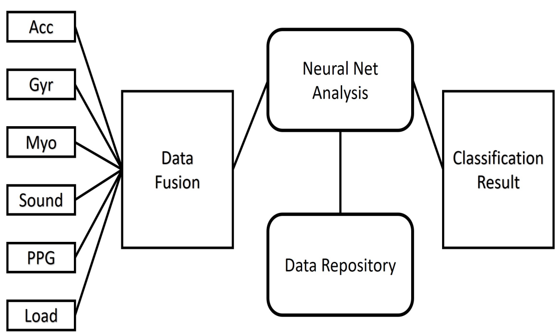


Figure 3: General Architecture of the enhanced VAG system.

The major characteristic of the VAG joint analysis is the trait of dynamic measurement, against still capturing like MRT or X-ray. The VAG measurement can be performed only in motion. Therefore, we propose and distinguish between two types of assessment, a fully controlled movement and the free movement.

The controlled movement is a setting like sitting in a chair and moving the limbs (Figure 4). The free movement describes the assessment during activities like walking, stair climbing, repetitive activities (e.g. cycling), or other activities of the daily living. The classification of free movement activities and their parameters is much more difficult that under controlled conditions. That is the reason we emphasis on the controlled assessment and will consider the mobile assessments subsequently in the future. The stationary concept (Figure 3) includes the usage of established sensors and additional sensors to complete the setting for a comprehensive assessment. The mandatory sensors for an enhanced vibroarthrography are:

- Ultrasound:
  Acoustic emission from human knee joints indicates, that healthy and unhealthy knees can be successfully distinguished during the sit to stand movement (Shark et al., 2010).

- Accelerometer:
  Assessing the ROM of the joint, detection of crepitus and other click and crack sounds (Toreyin et al., 2016).

These sensors will be extended by a net of additional sensors to improve the signal quality, to reduce the noise, to enrich the information, and to combine values with other parameters, e.g. vibration in relation to joint angle and angular velocity.

4.1 Improvements

The proposed concept includes several improvements as follows:

- Frequency Band
  The movements of the joint causes oscillations in various frequencies and intensities. Slow oscillations can be easily measured with acceleration sensors, higher frequencies are accessible by microphones. The proposed concept combines the two sensor types to be able to record the full range of frequencies. To ensure a reliable overlap, we propose to use the acceleration sensor in full range of sampling rate (e.g. up to 3.2 kHz by AXDL345) and the microphone (e.g. 20Hz to 44kHz).

- 3D Assessment
  Referring to the existing VAG database by Krishnan et al., our sensor system consists of multiple sensors with multiple axes, in comparison to only a one dimensional acceleration sensor.
  Furthermore, we will include the trajectory of the angle, to recognize a straight movement, torn ligament, or misalignment. Therefore, the integration of a radar sensor will be an option if the single use of acceleration sensors is not sufficient.
- Sensor Placement
  The coupling of the sensors to the joint is a challenge. In relation to ultrasonic assessment, a gel and cuff can be used to enhance the vibration signal flow. Furthermore, the vibration of a joint are transmitted also to the bones of the limb. Therefore, we will examine the signal transmission to the end of the related bones. We expect a leverage effect, that the vibrations of the e.g. knee are amplified at the foot angle. Similar to (Klemm et al., 2019) we may use extensions to enhance the vibration signals.
- Additional Sensors
  The concept of an enhances sensor network for VAG measurements includes additional sensors to examine supplementary effects, e.g. the mobility and strength of legs with unhealthy and healthy knees. To distinguish between joint disease and skeletal muscle disorder, the concept includes electromyography (EMG) for the measurement of muscle activity (Hollander et al., 2018) and PPG sensors to determine veins insufficiency by the light reflection rheography (LRR).
- Correlation to the Movement Angle
  The VAG database by Krishnan et al. contains only vibration data over time without any correlation of the angle of the joint. Our concept includes the simultaneously assessment of the joint angle.
- Joint Load
  We assume that the load free movement of the joint generates other vibration than a joint under stress, as proposed by (Andersen et al., 2018). Therefore, we designed a load measuring of the joint to receive a multi-parameter dataset.
- Execution Speed and Repetition
  The vibration of the joint differs by the execution speed of the joint motion (Kernohan et al., 1990). Therefore, we assess the vibration during certain motion speed. Currently, we are not aware if vibration vary in repetitions but this is a hypothesis that has to be examined in future work.
- Machine Learning and Artificial Intelligence
  The core of the VAG Sensing System bases on a classifier that consists of a neural network. Currently we propose a convolutional neural network (CNN) that enables an analysis of complex motions even during daily activities.

The improvements are combined into a sensor network with a multidimensional signal assessing and analysis platform.

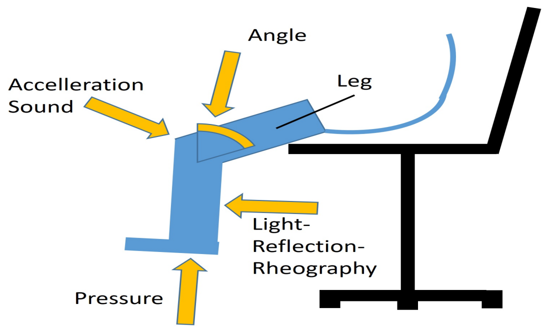


Figure 4: Heterogeneous sensors as a Sensor Network.

5 DISCUSSION

Signal analysis of mechanical bearings are state of the art for wear and abrasion estimation. The condition of human joints are currently only by interest when they hurt or if a major decline of mobility occurs. Since now, MRT, CT or ultrasonic examinations are procedures that are performed whenever a joint diagnosis is needed. These methods are expensive and provide only information recorded in a motionless state. In contrast, a dynamic assessment is an option to be used for further diagnostic. The VAG is a dynamic assessment tool that has the potential to become a very cheap diagnosis tool because the sensor data assessment is easy to perform, except the data analysis. Therefore, newest technological concepts in Machine Learning may be used for a powerful and reliable diagnostic. Unfortunately, classifiers based on convolutional or recurrent neural networks require a large dataset that does not exist so far. Existing data bases do not contain radiation related acceleration data and mixing all kinds of knee diseases together. For further research, we developed the concept for a comprehensive data assessment of VAG under the usage of a sensor network. With this concept, we are able to establish a comprehensive database that gives the basis for neural network classifiers.

We assume that VAG still has some limitations but we expect that the advantages outweigh the disadvantages. On one side, we are facing technical challenges like synchronization, easy handling for the patient with in a setting of self-assessment in the home environment. On the other side, VAG is an indirect measuring technique. We are not able to determine the thickness of a cartilage, but we measure the crepitus intensity. Therefore, it will be difficult to achieve a reliable relation between thickness and sound or degree of disorder or injury. VAG can be used as a gatekeeper technology and it is convenient to be used for a long term usage to obtain trends and progress states.

6 CONCLUSION AND FUTURE WORK

In the paper, we describe a new concept of using the technology of vibroarthrography (VAG) by using stationary and mobile assessment of vibrations of human joints during motion. Hereby, we describe the general concept of a stationary assessment system and outline the improvements. The analysis of the vibration pattern assessed with the enhanced VAG system enables a high sophisticate classification with neural nets and the discrimination of healthy or injured joints. Therefore, we propose to build up a comprehensive database, consisting of heterogeneous sensor data assessed by the enhanced VAG sensor network.

The future work will be the application of the concept and the implementation of a database. Furthermore, we will investigate the relevance of trajectories of the leg and the interplay of muscle strength, venous insufficiency, and joint disease. VAG did not found the respected dissemination or usage as a diagnosis tool so far, but we assume that the advantage of a harmless, easy to perform and cheap analysis leads to its establishment. We propose that not only injured but also artificial joints can be analyzed.

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