ACOUSTIC EMISSION MEASUREMENT SYSTEM FOR THE ORTHOPEDIC DIAGNOSTICS OF THE HUMAN FEMUR AND KNEE JOINT

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Abstract

Orthopedic diagnostics per DIN EN ISO 9000 ff requires methods of nondestructive process control. Acoustic emission (AE) signals allows the prediction of bone rupture and assessment of the tribological status of the knee joint. We have developed an adaptive AE measurement system named Bone Diagnostic System (BONDIAS), making the in vivo analysis of the medical status possible.

1. Introduction

Quality control in the orthopedic diagnostics according to DIN EN ISO 9000 ff requires methods of nondestructive process control, which do not harm the patient either by radiation or by invasive examinations. To improve health economy, quality-controlled and nondestructive measurements are needed in the diagnostics and the therapy of human joints and bones. Non-invasive evaluation method for the state of wear regarding human joints and the cracking tendency of bones is not established yet.

The analysis of acoustic emission (AE) signals allows the prediction of bone rupture far below the fracture load. The evaluation of dry and wet bone samples revealed that it is possible to estimate the bone strength from crack initiation and thus to predict the probability of bone rupture. Besides the fracture probability of bone, AE allows to assess the tribological status of the knee joint. Simple states of wear without inflammation can be separated from states of wear complicated by inflammation (arthritis). For the assessment of the tribological knee function and by the probability of fracture of the femur, an adaptive AE measurement system named Bone Diagnostic System (BONDIAS) was developed. This system makes the in vivo analysis of the medical status possible.

2. AE Assessment of Crack Initiation and Crack Propagation in the Human Femur.

Mechanical loading of the femur is accompanied by elastic strain. Due to differences in compliance of the compacta and the trabecular system of bone shear stresses arise in the interface of the compacta and the trabecular system, eventually leading to crack initiation. Different mechanisms of cracking were accompanied by different AE from human femora as shown in literature [1-6, 8]. An AE signal typical of crack initiation is shown in Fig. 1. It is characterized by a very short rise time and an exponential decrease of the amplitudes.

The assessment of crack initiation is very important in the healing process after the bone fracture, or during the implantation of an endoprosthesis of the hip, or in cases of osteoporosis. Equally important is the development over time of the threshold of crack initiation during the healing process or in the cause of a disease. For the assessment of crack initiation of the femur a certain mechanical load is afforded. The BonDiaS-System allows applying different ranges of...
motion and loads especially those, which are typical for the patient’s day-to-day life. These comprise e.g. rising from a chair, knee bending, climbing up or down staircases. From the medical point of view such mechanical loads are regarded as non-destructive although there is already crack initiation in the interface of the compacta and the trabecular system of the bone. These micro cracks seem to be essential for the physiological bone remodeling. For the description of the development of bone strength over time it is necessary to assess both the threshold of crack initiation and the conditions for crack propagation. For the evaluation of fracture toughness further examinations of the crack initiation and the crack propagation are necessary. Assessment of the geometrical structure by computer tomography (CT) in combination with an experimental calibration of compliance allows the evaluation of the fracture mechanics. The two thresholds of crack initiation and stable crack propagation, which are needed for this evaluation, follow from AE analysis.

![Fig. 1 Acoustic emission caused by crack initiation in the compacta-spongiosa interface.](image)

According to the AE analysis, stable crack propagation appears in the transit from area I to area II as demonstrated in Fig. 2. This graph shows the total AE counts according to the applied load. There is a clear distinction of the transition, which is defined as the load critical for cracking. Based on results gained from explanted femora these evaluations can be performed in vivo, now.

The fracture toughness can be calculated from:

$$K_{IC} = \sigma \sqrt{\pi a} f\left(\frac{a}{W}\right)$$

Here $\sigma$ describes the normal stress with respect to the crack plane and $a$ the depth of the crack. $f(a/W)$ is a correction function gained by calibration of compliance to take into consideration the individual femur geometry and the length of the crack, $W$. The values of fracture toughness are

- $K_{IC}= 220$ [N-mm$^{-3/2}$] at the transition from area I to area II,
- $K_{IC}= 330$ [N-mm$^{-3/2}$] at fracture load.

The normal stress $\sigma$ is calculated individually by FEM analysis based on CT data. To optimize the FEM analysis a variety of grid structures are tested at the moment.

This system is well suited to assess for each patient the individual critical load for cracking. To know these individual critical thresholds of bone cracking is the key to assess the bone strength e.g. in patients recovering from bone fracture or under therapy in cases of osteoporosis.
or during the implantation of a hip endoprosthesis. It is also the key for all those participating in sport activities to the limit of endurance or for those who have the training of bone strength in mind. Of course, it is necessary to apply the knowledge gained with this system in all the medical fields where structure and function of the human skeleton is affected or impaired.

Fig. 2: Accumulated momentum of acoustic emission over the applied bending load.

Fig. 3: AE from a knee joint during knee bending, correlated to the angle of knee flexion.

3. Surveillance of the Human Knee Joint

A natural center of the surveillance of joints is the analysis of the AE from joints moving under typical daily load. Here again, the typical loads comprise e.g. knee bending, climbing up or down stairs, but also ergometric examinations. The AE analysis of the knee joint clearly reveals cartilage lesions, arthritic degeneration of the knee joint with more or less inflammatory contributions and damage caused by the change of the inclination of the line of thrust [7-9]. Acoustic emission from the knee joint (Fig. 3) is registered by a sensor, which is fixed by tapes to the skin over the medial condyle of the femur (Fig. 4) during application of the natural load.

As shown in Fig. 3 the AE is registered over time (upper part of Fig. 3) and correlated to the angle of knee flexion, i.e., thin line in the diagram in the lower part of Fig. 3. The kinetics of load
and motion can reveal non-stationary characteristics, which can be typical of certain diseases. Knowing the kinetics of load and motion, the AE offers potential causes for the measured phenomena. Whether the medial or the lateral femoral condyles or both are damaged can be tested by changes of the distribution of load and by the concomitant registration of the emission.

Fig. 4 Position of an AE sensor at the medial femoral condyle during the measurement.

Fig. 5 AE from cartilage deformation in a healthy knee joint after the sudden change from a two-legs stand to a one-leg stand.

The AE analysis allows for a multifaceted assessment of joint defects depending on the range of knee flexion medial or lateral condyles can be changed thereby. A short rise time of the AE characteristic for cartilage defects is correlated to a low signal damping by the cartilage layers. If in that case a cartilage lesion can be verified such a signal is really indicative of a low thickness of the cartilage layer in the damaged area. To reach this diagnosis the individual damping characteristics of the knee cartilage have to be assessed. This information is drawn from a simple test. The instrumented patient is standing relaxed on the two legs and then he quickly raises one leg. The fast increase in load of the loaded leg also initiates reactions in the additionally loaded knee cartilage. Acoustic emissions typical of normal cartilage, of arthritis with more or less inflammatory contribution and of cartilage lesions are demonstrated in Figs. 5 to 7.
Figure 5 demonstrates the AE from a knee joint caused by cartilage deformation due to the sudden change from a two-legs stand to a one-leg stand. The intermittent cartilage deformation is of visco-elastic nature. The graph of AE over time shows a correlation to the thickness of the deformed cartilage. Short signal duration is indicative of a thin cartilage layer.

Acoustic emission from a cartilage lesion is shown in Fig. 6. Articulating cartilaginous counterparts literally “fall” into the cartilage lesion. In reality this process has to be considered as a sliding one. Sliding into the lesion (indicated by region 1) over the ingoing visco-elastic edge of the cartilage lesion is accompanied by a low energy transfer. The concomitant AE is of low energy and amplitude. Sliding out of the lesion, however, as shown in region 2, the outgoing edge of the lesion is strongly deformed. A higher volume of the cartilage is deformed visco-elastically with high energy. This is accompanied by AE with a long rise time representing both the sequence of motion and the deformation process of the cartilage. The latter is responsible also for this type of amplitude descent.

Fig. 6: Acoustic emission from a cartilage lesion.

The AE from an arthritic defect is represented in Fig. 7. Arthritic defects are characterized by different events in the course of AE. This can be a signal typical of cartilage lesions where needle-like signal peaks are superimposed. These signal peaks are usually due to stick-slip effects or to the interaction of bone structures in the contact areas.

4. Measurement System BONDIAS

The measurement system BONDIAS has been developed for the automated assessment and evaluation of the AE from the human femur and knee joint for the orthopedic diagnosis. Knee bending of a patient will release AE in high temporal resolution and well correlated to the angle of knee flexion. However, the physician is not left alone with a bundle of data and the task to evaluate the AE. He will get the relevant information concerning:
• Arthritic lesions in the knee joint: well characterized AE, singular events without a follow up of further emission.
• Acoustic emission due to elevated intra-articular friction caused by e.g. cartilage lesions, inappropriate surface roughness, a lack of synovial fluid or other defects: a plethora of continuous emission.
• Crack initiation in the femur: a burst type AE followed by continuous emission, which is typical of relaxation phenomena in the crack banks

The energy and the frequency of signals are mostly indicative of the originating events and important characteristics for the evaluation of defects. Added also is an analysis of the center of thrust under the foot, which reveals [uniformity/non-uniformity] of the motion.

5. Benefits for the Use in Medical Therapy

The non-invasive diagnosis is based on the analysis of AE caused by day-to-day motion and load in a well-defined manner. There are several advantages of this diagnostic procedure when compared with the established conventional methods:

• No pain is caused by this procedure.
• This procedure is non-destructive. Mechanical load even beyond the crack initiation threshold are typical of day-to-day life and necessary for the physiological bone remodeling to avoid the degeneration of the bone and joint system.
• There is no health burden through ionizing irradiation as is unavoidable with X-ray examination and CT.
• There is no danger of infection since this is a non-invasive examination.
• The time needed for the assessment of the acoustical emission and the validated analysis of data is of the order of seconds to minutes.
• The expenses for the AE measurement system are small compared to X-ray systems.
• The costs per examination including a detailed diagnosis are well below costs of other diagnostic procedures and there is no danger of causing further costs by infection as occurs with invasive methods, e.g. endoscopic examinations.
• Diagnostic (real time) monitoring of bone and joint training of e.g. sport professionals becomes possible.

References


