Acoustic Emission Measurement System for the Orthopedical Diagnostics of the Human Femur and Knee Joint

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1. Introduction

Quality control in the orthopedical diagnostics according to DIN EN ISO 9000 ff requires methods of nondestructive process control, which do not harm the patient neither by radiation nor by invasive examinations. To gain an improvement of health economy quality controlled and nondestructive measurements have to be introduced in the diagnostics and the therapy of human joints and bones. There is no non invasive evaluation method for the state of wear regarding human joints and the cracking tendency of bones yet established.

The analysis of acoustic emission 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 conclude from crack initiation to the bone strength and thus to predict the probability of bone rupture. Besides the fracture probability of bone acoustic emission 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 adapted Acoustic Emission Measurement System named **Bo**ne **Dia**gnostic **S**ystem (BONEDIAS) was developed. This system makes the in vivo analysis of the medical status possible.

2. Application of the acoustic emission analysis for the assessment of crack initiation and crack propagation in the human femur.

Mechanical loading of the femur is accompanied by elastical 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 acoustic emission from human femora as shown in literature [1-6, 8]. An acoustic emission 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.

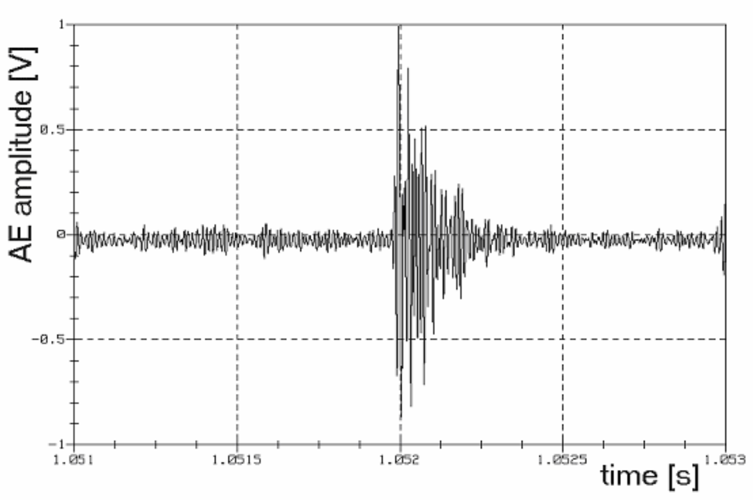

Figure 1: Acoustic emission caused by crack initiation in the compacta-spongiosa interface

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 BONEDIAS-System allows to apply 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 or unclimbing of stair cases. 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 stabile crack propagation which are needed for this evaluation follow from acoustic emission analysis.

According to the acoustic emission analysis, stabile crack propagation appears in the transit from area I to area II as demonstrated in fig. 2. This graph shows the total acoustic emission count according to the applied load. There is a clear distinction of the transit 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 σ describes the normal stress with respect to the cracking 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

- in the transient from area I to area II K_{IC}=220 [$Nmm^{-3/2}$]
- at fracture load K_{IC}=330 [$Nmm^{-3/2}$].

The normal stress σ 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 the patients individual loads critical 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 exercising sport activities to the limit of endurance or for those who have a 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.

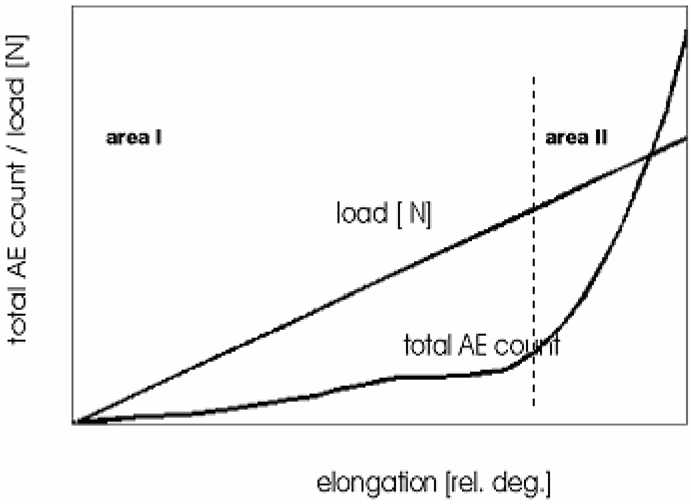

Figure 2: Accumulated momentum of acoustic emission over the applied bending load

3. Surveillance of the human knee joint

A natural center of the surveillance of joints is the analysis of the acoustic emission from joints moving under the typical daily load. Here again, the typical loads comprise e.g. knee bending, climbing or unclimbing of stairs, but also ergometric examinations. The analysis of acoustic emission from 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.

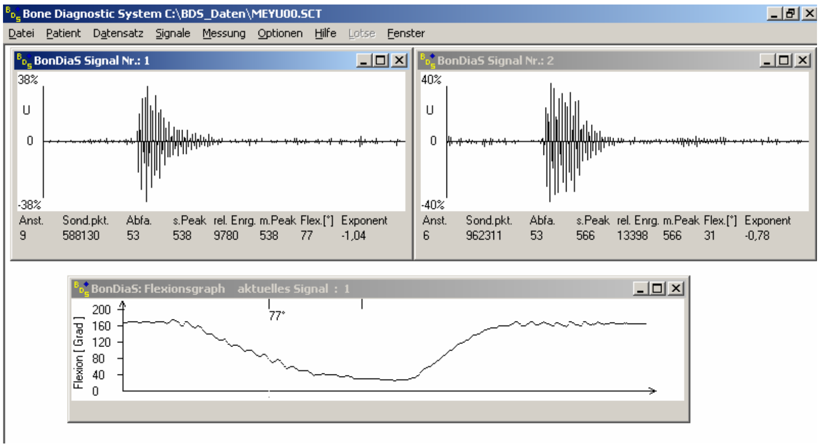

Fig. 3: Acoustic emission from a knee joint during knee bending, correlated to the angle of knee flexion.

Fig. 4: Position of an acoustic emission sensor at the medial femoral condyle during the measurement

As shown in fig. 3 the acoustic emission is registered over time - upper part of fig. 3 - and correlated to the angle of knee flexion - 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 acoustic emission 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.

The acoustic emission 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 acoustic emission 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 relaxedly by on the two legs and then he quickly raises one leg. The fast increase in load of the loaded leg initiates reactions also in the additionally loaded knee cartilage. Acoustic emission typical of normal cartilage or of arthritis with more or less inflammatory

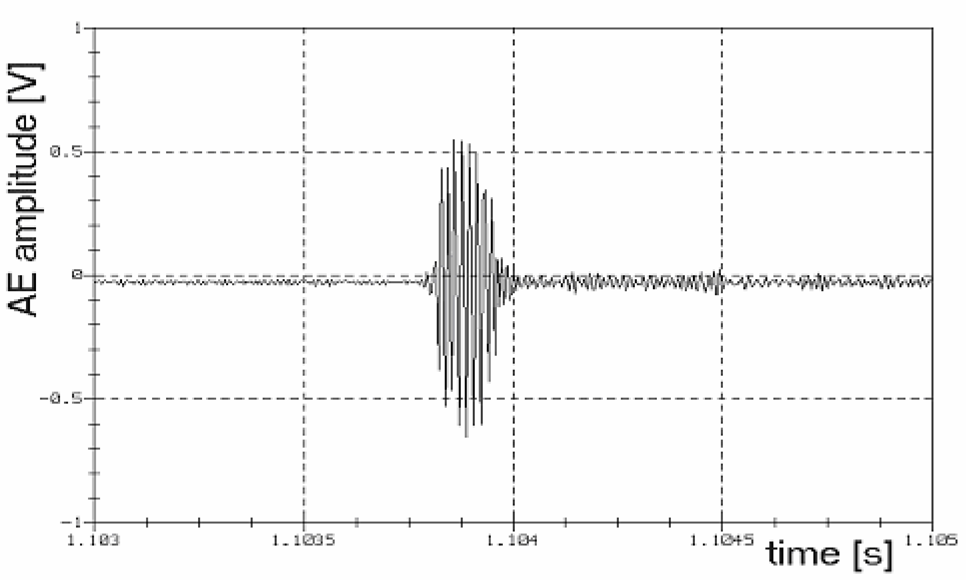

Fig. 5: Acoustic emission from healthy knee joint cartilage deformation after the sudden change from a two legs stand to a one leg stand.

contribution and of cartilage lesions are demonstrated in figures 5 to 7.

Figure 5 demonstrates the acoustic emission 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 acoustic emission 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 acoustic emission 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 acoustic emission with a high 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.

The acoustic emission from an arthritic defect is represented in figure 7. Arthritic defects are characterized by different events in the course of acoustic emission. 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.

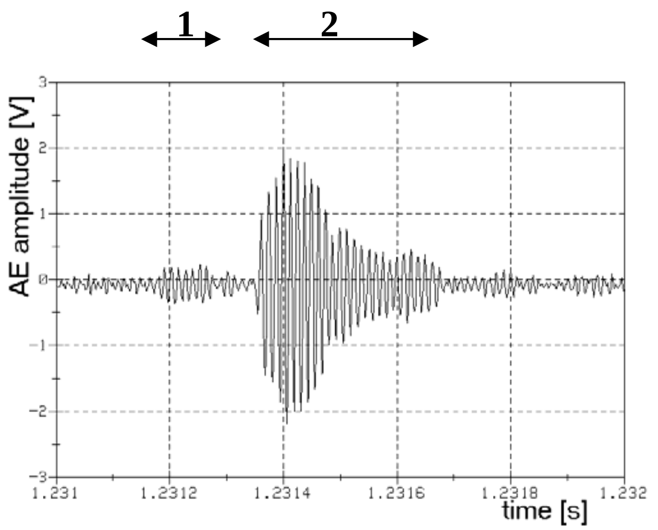

Fig. 6: Acoustic emission from a cartilage

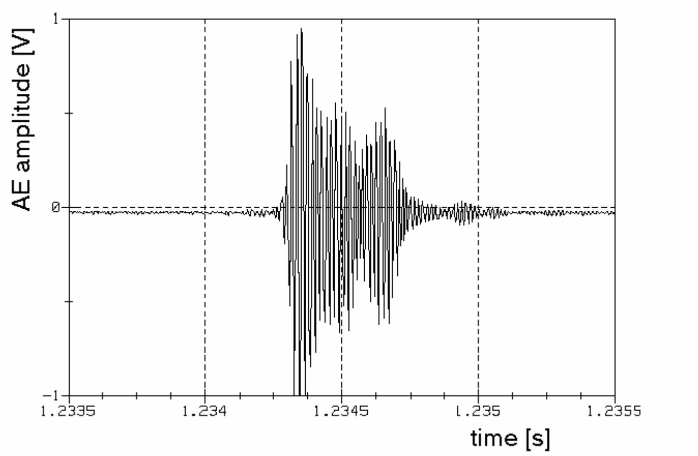

Fig. 7: Acoustic emission from an arthritic defect

4. Measurement System BONEDIAS

The measurement system BONEDIAS has been developed for the automatized assessment and evaluation of the acoustic emission from the human femur and knee joint for the orthopedical diagnosis. Knee bending of a patient will release acoustic emission 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 acoustic emission. He will get the relevant information concerning

- Arthritic lesions in the knee joint: well characterized acoustic emission, singular events without a follow up of further emission.
- Acoustic emission due to elevated intraarticular 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 of acoustic emission 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 is also 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 acoustic emission 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 remodelling to avoid the degeneration of the bone and joint system.
- There is no health burden through ionising 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 afford 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 Acoustic Emission Measurement System are small compared to X-ray systems.
- The costs per examination including a detailed diagnosis are well below costs of other diagnostical 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.

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