Nondestructive and Noninvasive Observation of Friction and Wear of Human Joints and of Fracture Initiation by Acoustic Emission

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Quality control in the orthopedical diagnostics according to DIN EN ISO 9000ff 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 therapy of human joints and bones. A non-invasive evaluation of the state of wear of human joints and of the cracking tendency of bones is, as of today`s point of knowledge, not 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.

Keywords: Acoustic emission analysis; noninvasive analysis; bone cracking; joint wear; bone strength

Introduction

The publication gives information about a new method of nondestructive and non-invasive observation of friction and wear of human joints by acoustic emission. The signs of wear in human joints are frequently detected in a progressive state by common procedures like X-ray investigations /1/. Possibly gross geometric changes can be recognised by x-rays. Endoscopic methods show lesions of all sizes and location. The effect of wear can not or only rarely be evaluated /2/. The acoustic emission of the frictional behaviour, however, allows an evaluation of the state of cartilage degeneration. The method indicates acoustically active defects in the human joint.

Hence an apparatus for testing the wear in the knee joint was developed, which makes it possible to simulate a more or less physiological roll-glide friction. A qualitative differentiation between damaged and undamaged joints has been achieved. Artificially set defects cause typical acoustic emissions in a reproducible form. Clinical tests with this acoustic emission analytical system which were performed in parallel to the commonly used diagnostic methods, showed that the analysis of acoustic emission allows a differentiation of joint defects and their consequences.

Measuring Principles

The technique used is the acoustic emission analysis (AEA) /3, 5/. Acoustic emission is based on the phenomenon that under load stored energy is released spontaneously by crack initiation and propagation. This is the so called burst type of acoustic emission, shown in figure 1.

Friction processes, too, cause acoustic emission. But the series of pulses are in the slope of the individual acoustic signal. This is the continuous form of acoustic emission.

In the case, that the cracking is accompanied by friction in already existing crack banks, a continuous acoustic emission with low amplitude and energy overlaps the burst signal.

The frictional behaviour and the gliding mechanisms in human joints, while moving under load, can be discriminated and analysed thanks to a well distinguishable form of emission.

This form of acoustic emission is shown in figure 2, corresponding to the physiological roll-glide motion of a human knee joint with known lesions under well defined load. The long rise time of the acoustic signal is obvious. The slope of the signal does not follow an exponential course.

Measuring system

First of all, the measuring device has to be adapted to the characteristic signals of acoustic emission generated by crack initiation and propagation or by frictional behaviour of articulation surfaces with regard to the surrounding noise. It turned out to be favourable to select from the broadband acoustic emission signal a band of frequencies where the difference of the signal amplitude and the interfering noise amplitude is as large as possible. In the examples given here a resonance frequency of the transducer of 100 kHz was chosen. Introductory tests showed that the following testing method was the most favourable. The transducer was fixed directly on the bone in the fracture- and friction-tests of the explanted bones and directly on the surface of the skin in the in-vivo-tests of patients. The measuring system is shown in figure 3.

The transducer was an undamped piezoelectric converter, connected to an amplifier with an integrated impedance converter. The amplified acoustic signal was filtered by a band-pass within the resonant frequency band of the transducer. Depending on its intensity the signal was further amplified and then evaluated according to the test query.

To assess whether the acoustic emission really corresponded to bone cracking or to the state of integrity / extent of damage of articular cartilage, the results of acoustic emission analysis from loaded explanted bones / joints were compared to the histological fracture morphology of these bones and the quality of joint surfaces.

The assessment of acoustic emission from damaged knee joints in vivo was completed by the endoscopic inspection of the examined knee. A typical data registration and processing-system is also shown in this figure.

Detection of joint friction

First of all the acoustic signals of a more or less physiologically moving knee joint had to be evaluated. With explanted human femur condyles, which were pressed against polymeric counterparts simulating the tibial plateau, the roll-glide movement of a knee joint under a certain load and then with defined damage of the joint surfaces were simulated in a loading apparatus, shown in figure 4.

The femur condyles were embedded in a resin with a low polymerising temperature, so that the material properties of the bones and joints were not altered.

The testing apparatus enabled a realistic simulation of joint`s loads during knee bending. The acoustic emission amplitude distribution of the signals were the same as those seen in patients in vivo. The friction of an undamaged surface caused acoustic emission which could not be discriminated from the noise level.

For a comparison between artificial damage and normal damage in knee-joints a field test was carried out among volunteers of the faculty members and students of the Technical College Fachhochschule Gießen-Friedberg and patients with well-known joint-defects of the orthopaedic clinic Passauer Wolf.

A test was built, which included tasks of the daily life, as there are:

- going upstairs and downstairs
- jump down from a platform 40 cm above the ground
- sitting down on a chair and standing up
- walking on an instrumented path
- cycle-ergometer-test with instrumented pedals for the registration of the load distribution at the sole of the foot and
- knee-bends

Figure 6 shows typical sequences of acoustic emission in vivo of joint surfaces with clinically well characterized types of cartilage damage during knee-bending of the patients. The defect of each knee is indicated by a flexure dependent acoustic emission. The acoustic emission was recorded from 125 knees. The ages of participants ranged from 20 years to 58 years, of which students between 20 and 30 years represented the major part.

The acoustic emission is reproducible, which is shown in figure 7. A bicycle ergometer-test of a patient is demonstrated with a well known cartilage-defect - a superficial cartilage lesion a little more pronounced than in figure 6a - . The test was repeated three times. It yielded obviously the same results under different loading cycles. The defect was indicated at the same bending-angle of the knee as here the acoustic emisssion was just about the same. The test confirmed the results (not shown here) gained from previous tests on explanted joints exvivo with respect to form and intensity of the signals. There was a clear correlation between the extent of the damage and the acoustic emission.

Also figure 8 points out that acoustic emission diagnostic gives reproducible information about artificial defects in the human knee under artificial load and movement. Figure 8 shows the results of a bicycle-ergometer-test as described in figure 3. In this test apparatus acoustic emission can be evaluated by additional information about pedal load, load distribution in the pedalfield and angle of pedals for an improved diagnostic of defects in a human knee.

On the left side in figure 8 the time relation of pedal load and pedal angle are shown and the load distribution on the pedal field, the main information of symmetry of load and regularity of movement and on the right side information about acoustic emission amplitudes in correlation to angle of pedals and pedal load. The maximum of acoustic emission amplitudes corresponds to artificial angle of pedals and artificial pedal load. This information allows the location of the defect and describes the critical load in the knee. Here we define that load as the critical load which leads to acoustic emission from a defined joint cartilage area at a defined angle of knee bending in all consecutive cases of knee bending. The amplitude distribution of acoustic emission and the amplitude-time relation gives further information about the mechanism of damage. It is possible to attribute the location of the defect to the medial or lateral condyle by an awkward position of the foot during the test.

This testing method allows in principle not only the detection of local damage and their consequences on the load distribution in the knee. It can give further information whether a defect has an effect on the roll-glide mechanism in the knee. Under pain each person seems to change the load distribution to lower the pain in the damaged zones, so that the damaged area is not further loaded.

Crack initiation and propagation in human bones

Typical loading conditions like knee-bending, cause a time resolved acoustic emission with a long rise time and a long decay with a non exponential time course. There is another type of acoustic emission with a short rise time and an exponential decay, which is typical of crack initiation and propagation in human bone. This is the so called burst-type of acoustic emission. Stored energy is released suddenly. This could be observed in knee bend tests, where besides acoustic emission typical of frictional processes the acoustic emission described above occurred.

For a clear proof of crack initiation thresholds in bones, whole load cycles up to the bone fracture have to be under a complete acoustic emission check. The tests on explanted human femora were stopped after the registration of the first acoustic emission. Areas which showed maximum load according to an accompanying Finite-Element-Calculation, were tested for first cracks.

The testing apparatus with an examined and cracked femur is shown in figure 9. The middle section of a femur can be tightly mounted and fixed as shown in figure 9a in the fixed clamp (C_F) on the left side and the loose clamp (C_L) on the right side of the cartoon. Torsional load is applied by turning of the wheel (W) of the loose clamp (C_L). Flexural load is applied by rotation of the clamp $C_L$relative to the clamp C_F around the turning centre J. Torsional and flexural load are applied together**.** Application of a vertical line at a radius of 55mm on wheel (w) produces torsion and the moment value is given by the product of the force and the radius of the wheel, as shown in Fig 9a. In the head of the diagram of figure 9a you see the section of the bone mounted in the loading apparatus. Indicated by vectors are the torsional (T) and flexural moments (M_b) of the bone. Figure 9b shows the final state of the experiment after bone rupture.

For the detection of first cracks, histological samples were prepared and evaluated by light and fluorescence microscopy. In order to test whether the first acoustic emission was due to irreversible damages, the samples were loaded again up to the maximum load of the previous load cycle and then further. The occurence of burst type acoustic emission, indicative of crack initiation and propagation, happened only after exeedingthe previous maximum load (Kaiser-Effekt), which points out the irreversible damage /4/.

With increasing load, up to the bone fracture, the acoustic emission can be correlated to the crack initiation and propagation. Friction free loading of bones, however, is a prerequisite for correct acoustic emission tests. Interfering noise has to be decoupled from the specimen. A typical loading diagram in correlation to acoustic emission is shown in figure 10.

The bone was subjected to a continuously increasing load. Depending on the load two characteristic areas could be distinguished in this figure. In area I no acoustic emission was registered until the development of first cracks. Histological samples from tested bones showed microcracks in the transition area of compacta and trabecular bone.

It is thought to be an evidence for the irreversible damage of explanted bones, that after relief of the bone more acoustic emission occurred only after surpassing the previous maximum load. This could be shown in successive loading series, as long as the load was relatively low in comparison to the fracture load.

In area II not only an acoustic emission based on crack propagation could be observed, but also a continous acoustic emission caused by friction of the already existing crack banks. In addition the acoustic emission of the fracture is shown. It is obvious that the fracture is marked by an increase of events. During cyclic loading in this area the continuous type of acoustic emission (friction of crack banks) generally occurred already below the maximum load of the previous load cycle.

These tests have shown that it is possible to get information as to crack initiation far below the fracture load of the bone. The method has to be regarded as a non destructive and non-invasive testing method, where the required loading is of the same order as the usual daily load cycles. Hence it seems to be ideal to determine the bone strength via the analysis of microcracks and their acoustic emission in bones of patients in sequential tests.

A typical signal sequence can be seen in figure 11.The figure 11c shows two different types of acoustic emission. The first signal (time 3.9395 s) exhibits with a short rise time and an exponential decay a burst type of acoustic emission typical of fracture whereas the second signal (time 3.94053 s) with a long rise time and a non exponential decay is typical of crack bank friction. This is a typical succesion of acoustical events during crack propagation. A phase of relaxation is always followed by cracking. The greater the extent of damage the more the stress peaks in the cracking ground are minimized by crack branching and the more the crack bank friction occurs followed by new local cracks.

Conclusion

The acoustic emission tests on human joints and bones led to the conclusion that

- an evaluation of the state of wear and friction of human joints under physical strain is possible. - As figure 7 clearly shows there is a typical acoustic emission –long rise time and non exponential decay - on successive cycles of joint loading at the same angular position.-

- crack initiation in human bones can be detected and the fracture mechanism can be described. - As figure 11 demonstrates there is a burst type of acoustic emission with a short rise time and an exponential delay, which is typical of material cracking in general and also of bone cracking.-

Captions

Fig. 1. Burst type of Acoustic Emission – caused by bone fracture –

Fig. 2. Acoustic Emission caused by friction during knee-bending

Fig. 3. AE Measurement with processing system - Bicycle Ergometer Test–

I - AE measuring system

II - bicycle-ergometer –load and movement system

II - external data for characterization and interpratation of test results

Fig 4. Loading apparatus for simulation of roll-glide movement of a knee joint

Fig. 5. Test situation of going downstairs

(transducer is coupled to the skin of the knee)

Fig. 6. AE of different cartilage damages during knee bending

a – superficial cartilage lesion

b – stick-slip caused by superficial cartilage lesion

Fig. 7. AE of cartilage damage

Indication of the defect – a *superficial cartilage lesion - in three different tests at the same knee-bending angle*

Fig. 8. Bicycle-Ergometer-Test of a patient with artificial cartilage damage in the knee

a – Pedal load versus time

b - Angle of pedal versus time

c – line of load distribution at the sole of the foot

d – AE – amplitude versus the angle of pedal

e – AE – amplitude versus the pedal load

Fig. 9 Testing apparatus for combined bending and torsion of human femura

a – section of the bone mounted in the loading apparatus

b – final state of experiment

Fig. 10. Combination of a graph of load and of total AE count to the relative shift of the fixed clamp C_F against the loose clamp C_L. The relative shift of the two clamps can be correlated to the load of the bone fixed by the clamps. Area I refers to a phase of bone loading accompanied by a low increase in total AE counts. Area II describes a phase of bone loading accompanied by a steep increase in total AE counts

Fig. 11. AE of crack propagation and accompanied crack bank friction of a human femur

a - AE of a femur with combined torsion and bending load

b - Total acoustic emission count with information about the increase of fracture

c - Higher resolution of AE at the point, which is marked by an arrow above

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Acoustic Emission

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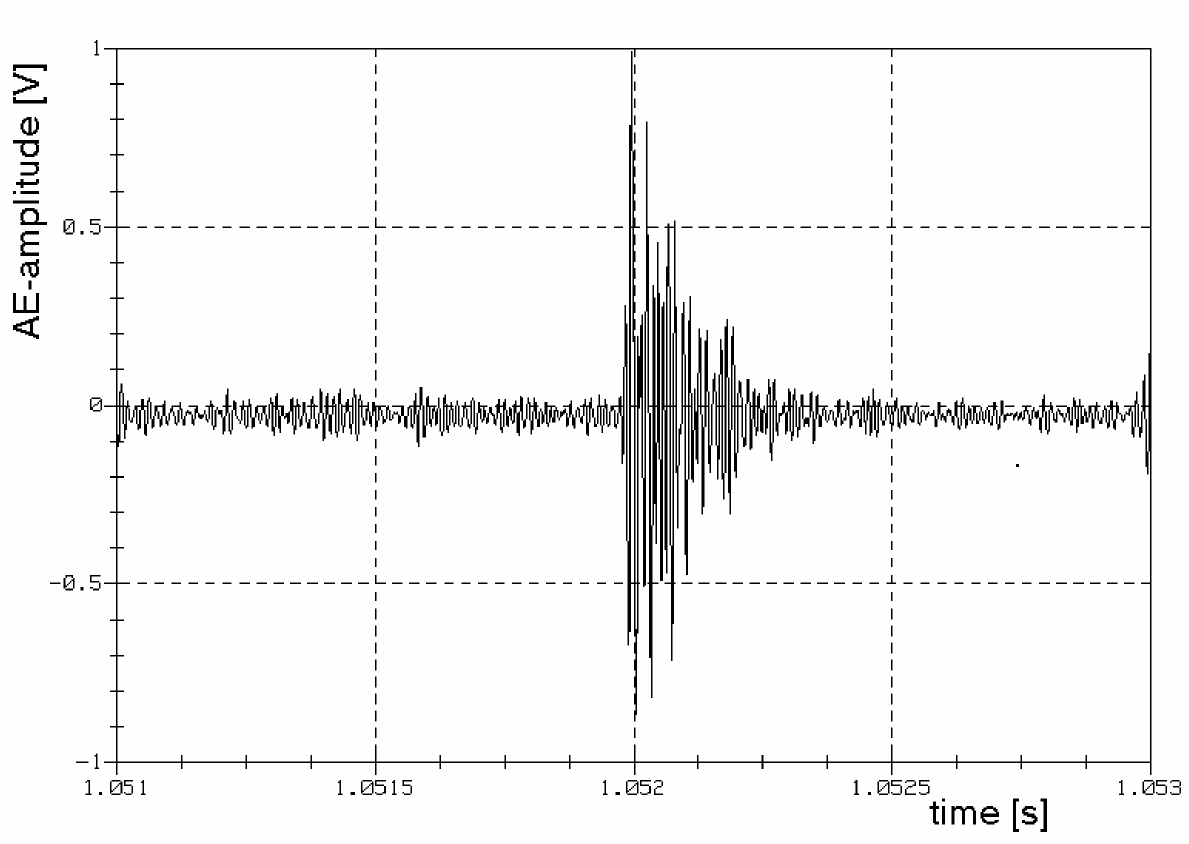


Fig. 1

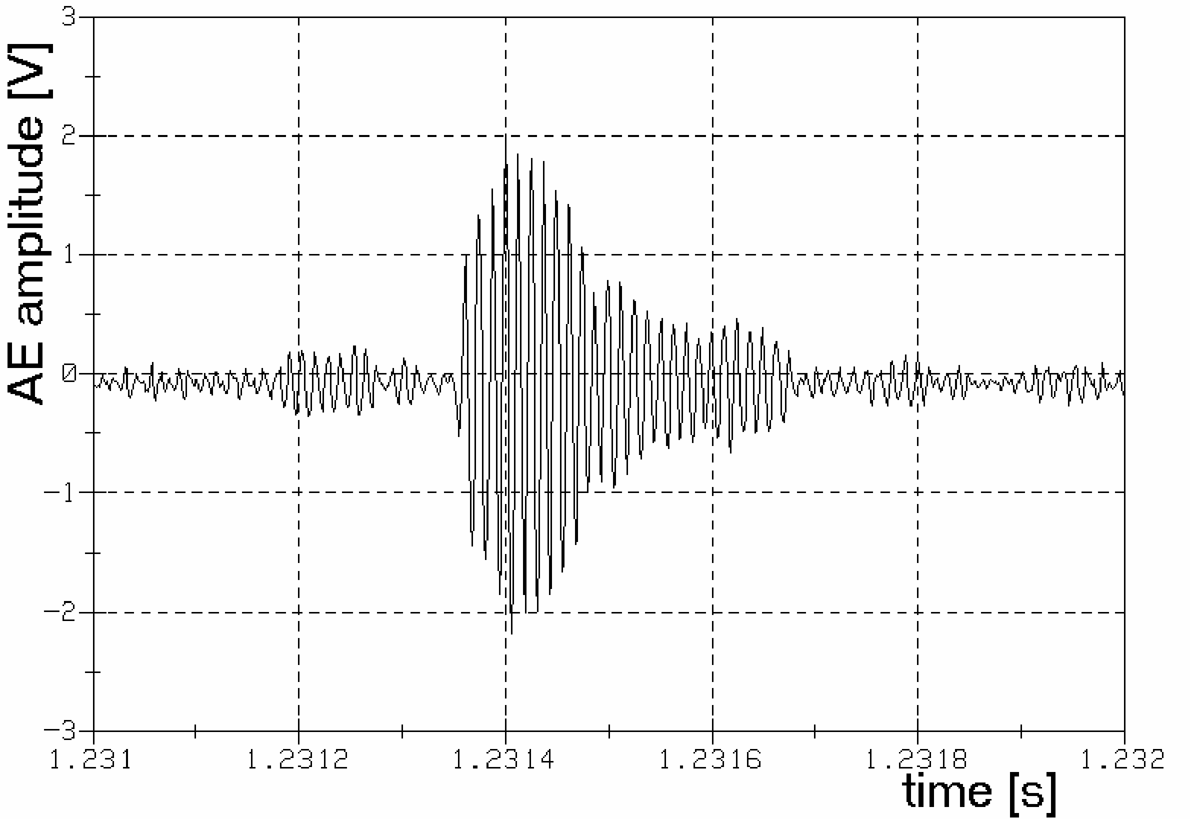

AE amplitude [V]
3
2
1
0
−1
−2
−3
1.231
1.2312
1.2314
1.2316
1.2318
1.232
time [s]

Fig. 2

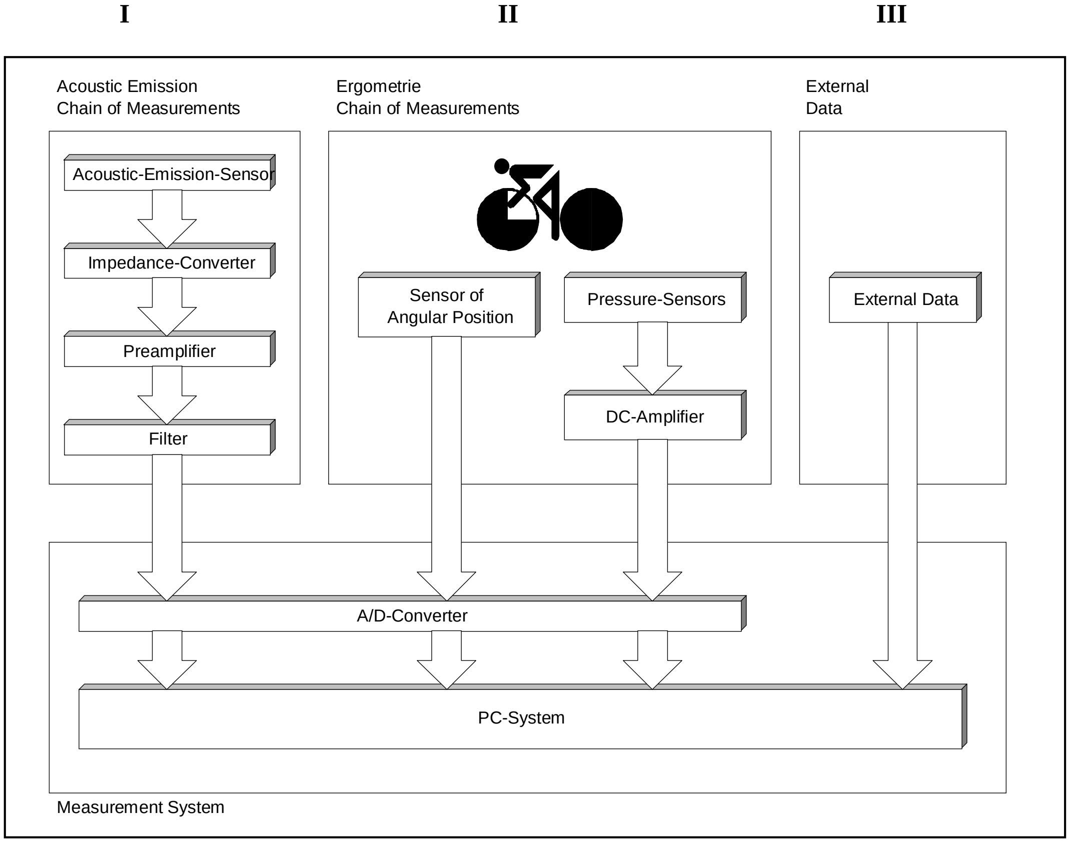

I
II
III
Acoustic Emission Chain of Measurements
Ergometrie Chain of Measurements
External Data
Acoustic-Emission-Sensor
Impedance-Converter
Preamplifier
Filter
Sensor of Angular Position
Pressure-Sensors
DC-Amplifier
External Data
A/D-Converter
PC-System
Measurement System

Fig. 3

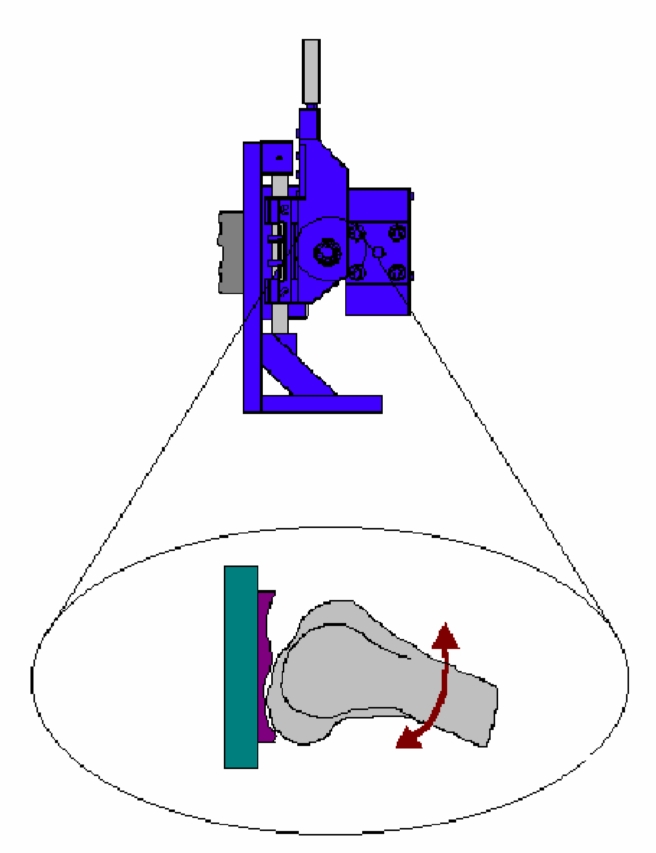


Fig 4

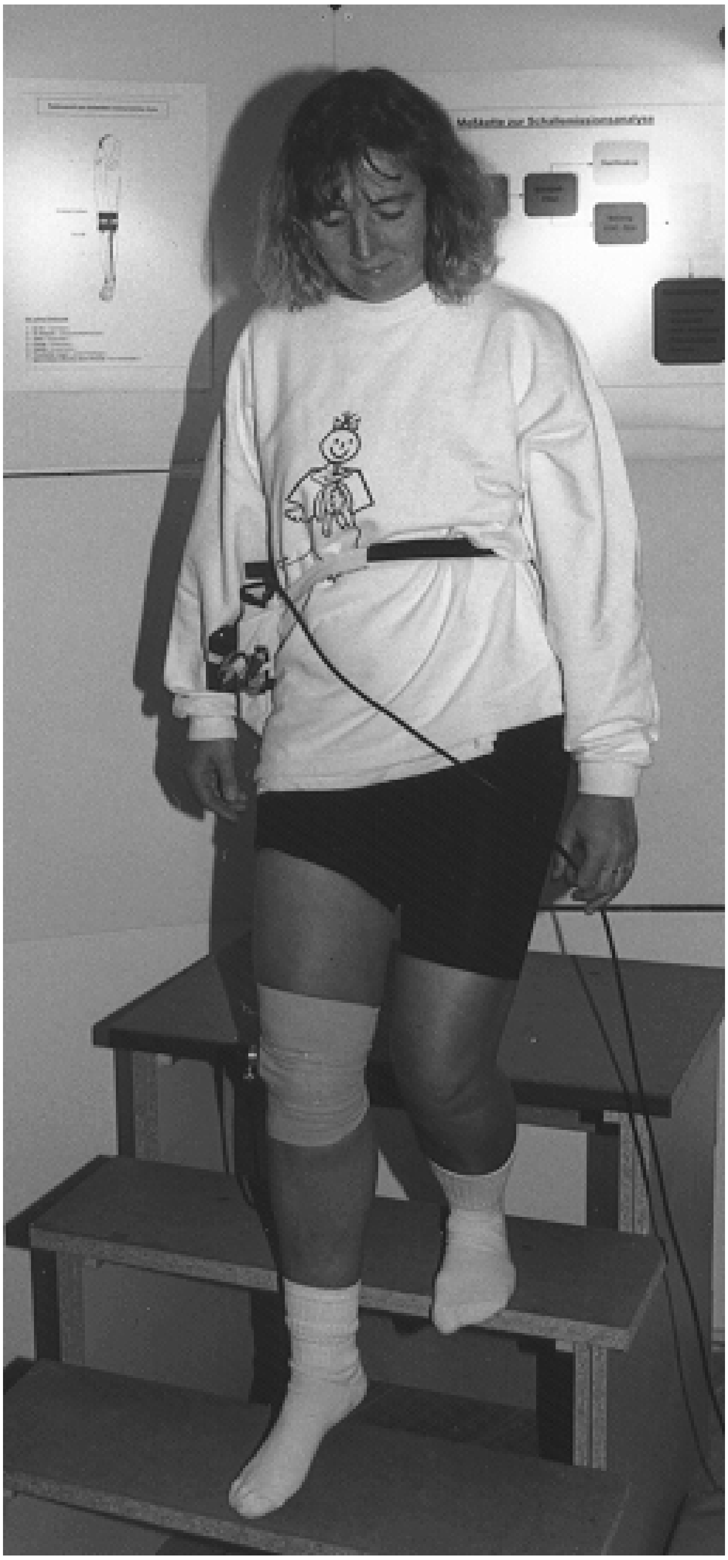
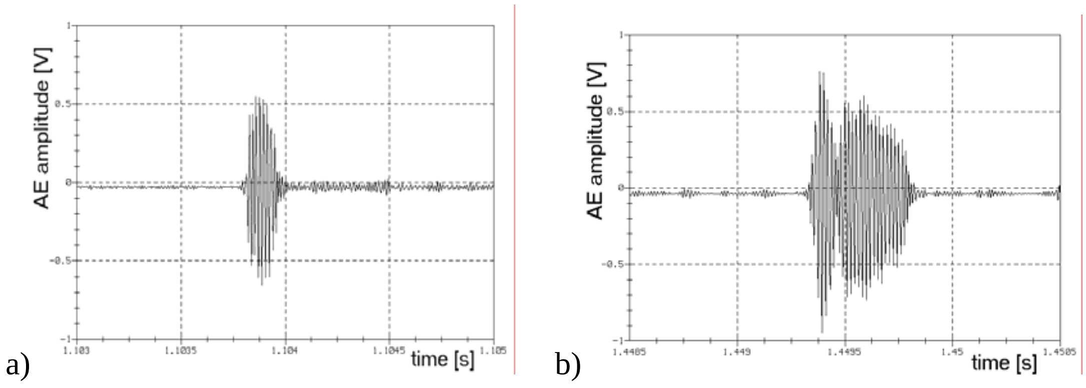


Fig. 5


AE amplitude [V]
1
0.5
0
-0.5
-1
1.103
1.1035
1.104
1.1045
1.105
time [s]
AE amplitude [V]
1
0.5
0
-0.5
-1
1.4485
1.449
1.4495
1.45
1.4505
time [s]

a) b)

Fig. 6

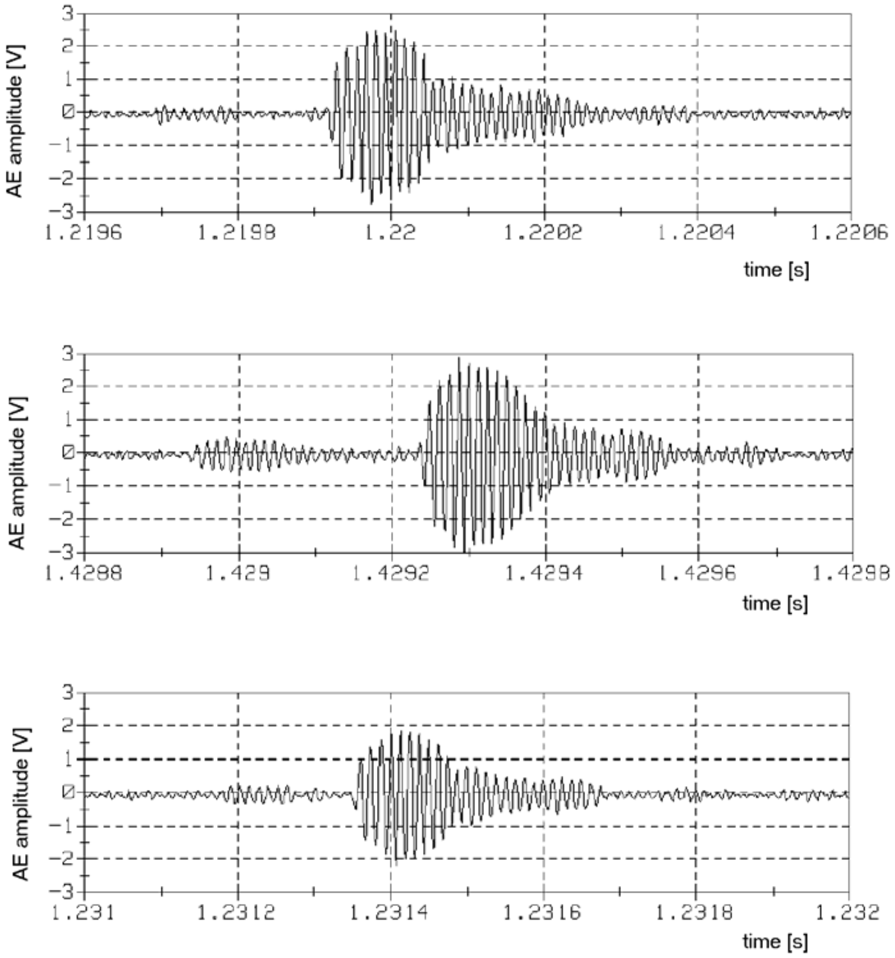

AE amplitude [V]
3
2
1
0
−1
−2
−3
1.2196
1.2198
1.22
1.2202
1.2204
1.2206
time [s]
AE amplitude [V]
1.4288
1.429
1.4292
1.4294
1.4296
1.4298
time [s]
AE amplitude [V]
1.231
1.2312
1.2314
1.2316
1.2318
1.232
time [s]

Fig. 7

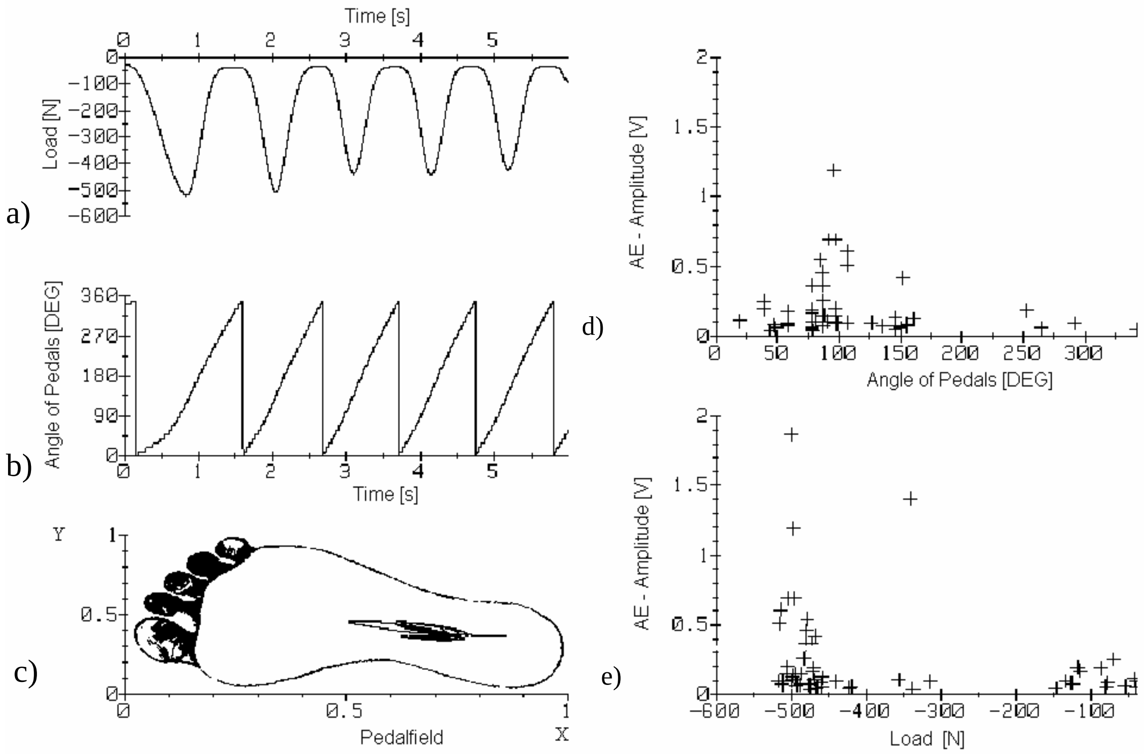

a)
Time [s]
0
1
2
3
4
5
Load [N]
0
-100
-200
-300
-400
-500
-600
b)
Angle of Pedals [DEG]
360
270
180
90
0
Time [s]
c)
Y
1
0.5
0
0.5
1
Pedalfield
X
d)
AE - Amplitude [V]
2
1.5
1
0.5
0
0
50
100
150
200
250
300
Angle of Pedals [DEG]
e)
AE - Amplitude [V]
-600
-500
-400
-300
-200
-100
Load [N]

Fig.8

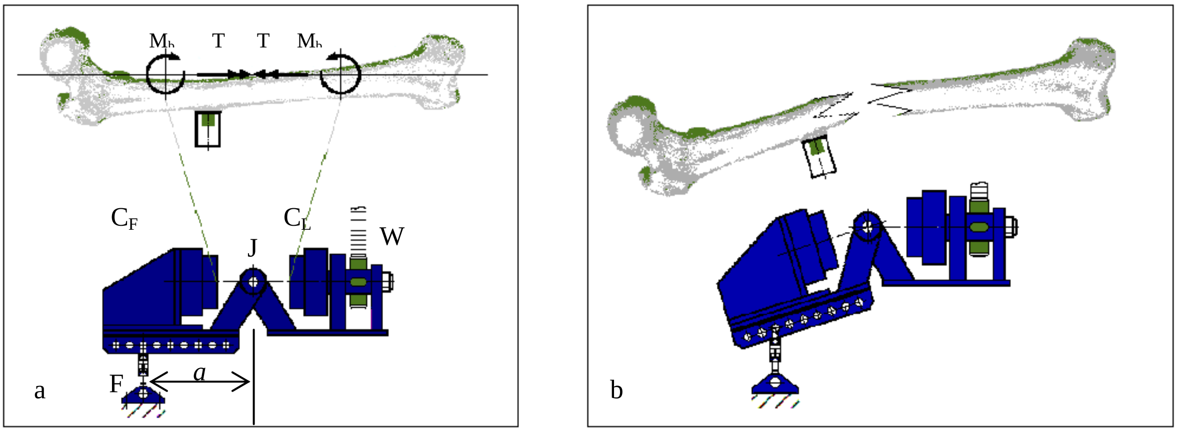


Fig. 9

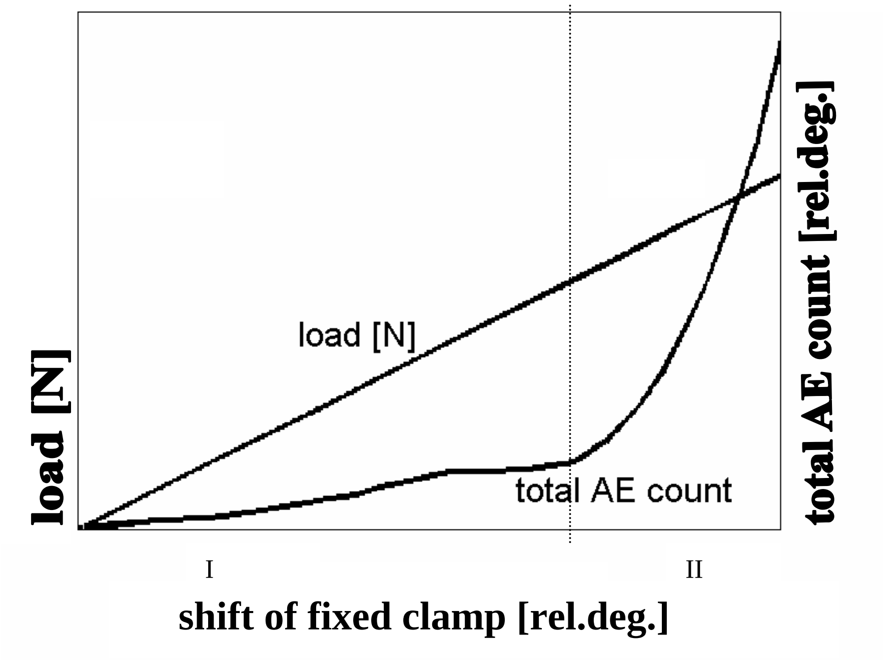

load [N]
total AE count [rel.deg.]
load [N]
total AE count
I
II
shift of fixed clamp [rel.deg.]

Fig. 10

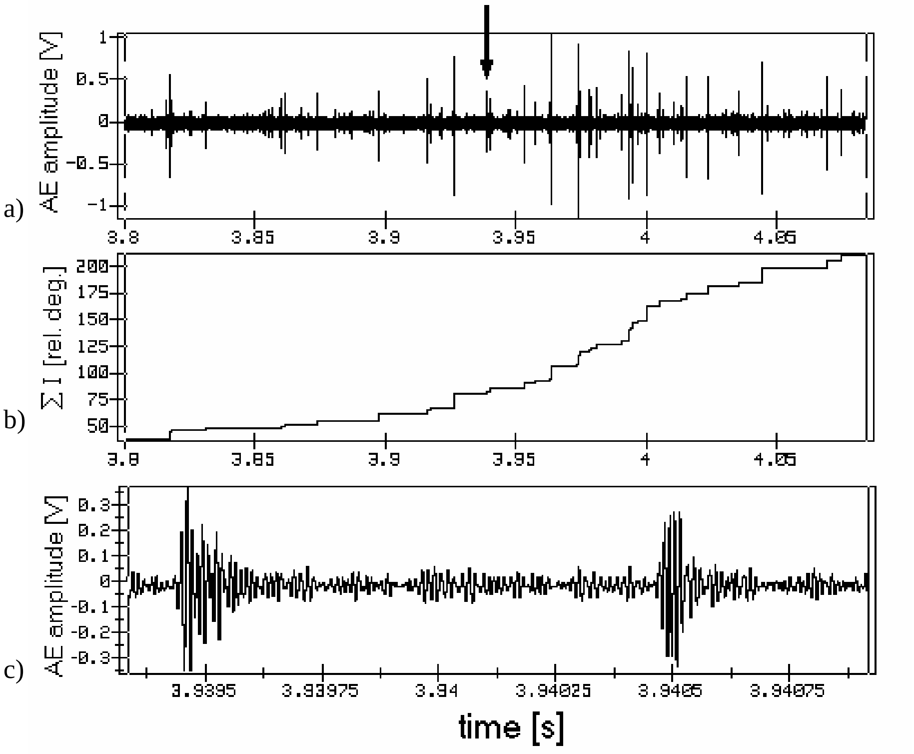

a)
AE amplitude [V]
1
0.5
0
-0.5
-1
3.8
3.85
3.9
3.95
4
4.05
b)
∑ I [rel. deg.]
200
175
150
125
100
75
50
3.8
3.85
3.9
3.95
4
4.05
c)
AE amplitude [V]
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
3.9395
3.93975
3.94
3.94025
3.9405
3.94075
time [s]

Fig. 11