Detection of Defects in the Human Skeletalsystem and Production of Failure Optimized Artificial Bone Applying Acoustic Emission Analysis (AEA)

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Abstract. AcousticEmission Analysis using resonant sensors was applied to diagnose human knee joints. Broadband sensitive sensors were examined whether they offer the same diagnostic accuracy. It is of key importance to know the cracking threshold in the human femoral bone especially in cases of disease and of healing bone after bone fracture. Cracking threshold and fracture kinetics were assessed in donated human bones. Bone explants are not available in arbitrary numbers and each bone is individually equipped with respect to geometrical structure and material behaviour. That is why there is such a great need for artificial bone. Exploiting acoustic emission analysis, new artificial bones are under development which resemble natural bones with respect to shape, structure and fracture kinetics.

Introduction

Due to a variety of reasons increasing damage and destruction of the cartilage of the human knee joint and of the patella can develop. Destruction of the articulating surfaces is often accompanied by painful reduction of joint function calling for medical treatment. To safely diagnose types and localisations of lesions / damages, imaging procedures and even more invasive arthroscopies are performed. Acoustic emission analysis (AEA), which does not exploit irradiation and is non-invasive, has been developed as diagnostic tool for orthopaedists for the earliest possible detection of cartilage lesions/ damage in the knee joint and for crack formation in the femur of patients under day to day load, like climbing stairs, rising from a chair or knee bending. After extensive initial research resonantly assessed (100kHz) acoustic emission was sampled from donated human undamaged or from knee joints with well defined damages to find and separate those signals typical of joint cartilage damage and those typical of crack initiation and propagation in bone [1,2]. Broad band sensitive sensors in comparison to resonant sensors are used to assess AE from probands without joint damage and from patients with known joint damage to get information whether the sensor type has influence on the diagnostic safety.

For the diagnostic of joints with conventional methods (MRT, CT, arthroscopy) the joint is not loaded. Contrary to AEA, the conventional methods could be harmful to the patients health. For the application of AEA the knee joint has to undergo a well defined movement and load. It is a great advantage of this method that only actively sound emitting sources are detected, these are lesions or damages which are placed directly in the line of load transfer. These damages are detected and will be passed by each step the patient takes, resulting in increasing cartilage damage and often in increasing pain. Therapies and corrective medical devices can change the patients movement characteristics in a way that the line of load transfer is moved so that it passes no longer through areas of cartilage damage. Therefore, AEA is able to evaluate therapeutical outcomes.

The cracking behaviour of human donated femora with or without damages due to bone diseases was assessed with AEA and compared with the cracking behaviour of artificial femora. This was the start of series of examinations to generate artificial femora with reproducible failure kinetics. The artificial femora will be tested under usual day to day loads and evaluated using morphometrical analysis of the fracture surfaces and AEA of the fracture kinetics.

1. Assessment of cartilage damage of the human knee joint and of crack formation thresholds in human femora using resonant or broadband-sensitive sensors

Resonant sensors (100kHz) are spacious and heavy due to physical reasons and there are limits for their use at the moving knee. In former examinations only resonant sensors were applied. When small-volume broadband-sensitive sensors are applied their stabile fixation at the knee joint is much easier, but the digital narrow band-filtering of the signals results in an unfavourable signal-noise ratio [1]. It has to be examined whether the evaluation of joint damages with the two types of sensors is comparable. This is necessary because the clinical examinations performed earlier used the resonant sensor.

Defects in the human knee joint are often based on arthrosis and cartilage lesions. These defects cause the most orthopaedically relevant damages in the human skeletal system beside problems of the hip joints and the vertebral column. It is only consequent, therefore, to make AEA mandatory for the diagnostic of knee joint defects beside the conventional roentgenographic and endoscopical methods [3]. Due to the method, AEA is the only diagnostic tool to detect actively emitting damaged regions of a loaded joint since acoustic emission is caused by defects in a moving loaded structure.

Due to physics, radial and axial width of a resonance sensor are determined by the afforded resonance frequency, which results in a spacious body at 100 kHz resonance frequency. Broad band sensors can be much less spacious when the signal to noise ratio at 100kHz is acceptable and the sensitivity after amplification complies with the demands. Acceptance of AEA in medical diagnostics is increasing when the size of the sensor decreases. Examinations of diagnostic safety of AEA either using resonant or broad band sensitive sensors follow.

The sensor is attached to the carefully depilated skin over the lateral femoral condyle by a well defined pressure which is generated by mild evacuation of the suction cup surrounding the sensor which is effected by a suction pump. The sensor is coupled to the skin applying an ultra sound couple gel approved for clinical use (Fig.1)

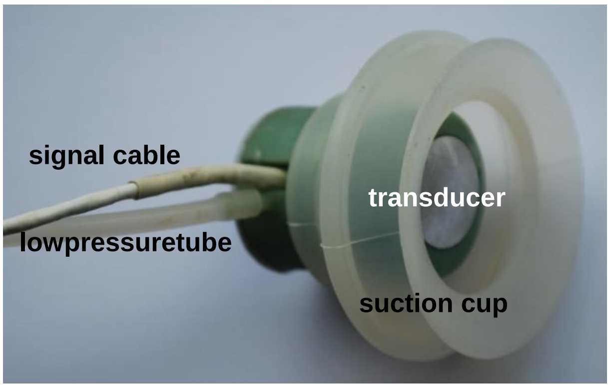

Fig. 1 Sensor with suction cup for a well defined sensor attachment.

The skin over the lateral femoral condyle was found to be most appropriate for attachment of the sensor because subcutaneous tissues are thin and the least attenuation of acoustic emission was found. For the assessment of the knee joint angle (angle between femur and tibia/fibula) a position sensor is used and built in the measuring system which is tape-fixed to the out side of the thigh under measurement. A proband in action with a fully equipped measuring system is shown in fig. 2.

Fig. 2 Proband in action equipped with the measuring system (emission sensor coupled to lateral femoral condyle; measuring device including the position sensor coupled to the proximal thigh)

2. Run of experiments

2.1 Examination of patient knees

Before the examination the patient has to keep the knee considered for diagnosis in an unloaded state for at least 30 minutes to allow for cartilage relaxation and for back flow of synovial fluid into the knee joint which had been forced out before due to load. This is necessary to get reproducible acoustic emission from knee joints. As individual load patients/ probands will carry out e.g. three successive knee bends within 10 seconds. The course of emission amplitude over time is displayed in correlation to the angle between femur and tibia/fibula. Only emission surpassing a trigger threshold well above the electronic noise is counted. For the comparison of resonant and broad band sensitive sensors, both sensors were simultaneously attached to probands/ patients knees and affected by the same emission. One sensor was attached medially to the knee, the other laterally. A second measuring cycle followed where the sensor positions were exchanged.

2.1.1 Knee joint defects

Lesions and arthritic damages cause acoustic emission where new emission typically appears within the time of decline of the foregoing emission. The type of emission is due to friction and is called “continuous emission”. A typical emission assessed with the resonant sensor is shown in fig. 3. It displays the course of emission amplitudes over time due to friction in a cartilage lesion. Differences in peak height between entering into and sliding out of the lesion point to a non-symmetrical contour of the lesion in direction of the movement. The individual processes generating the emission cannot be further discriminated.

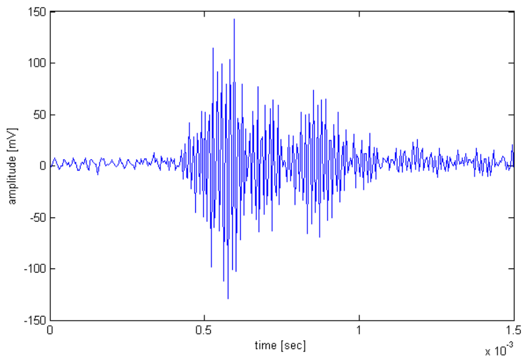

Fig. 3 Continuous acoustic emission associated with a cartilage lesion in a human knee joint (resonant sensor: 100kHz)

2.1.2 Crack formation in the human femur

Crack formation in the human femur is a discrete process causing burst signals with an exponential decline (Fig. 4). These bursts can occur during knee bending due to different types of loading. First crack formation in the femur usually will arise due to the shift in the elastic moduli between compact bone and trabecular bone effecting shear load.

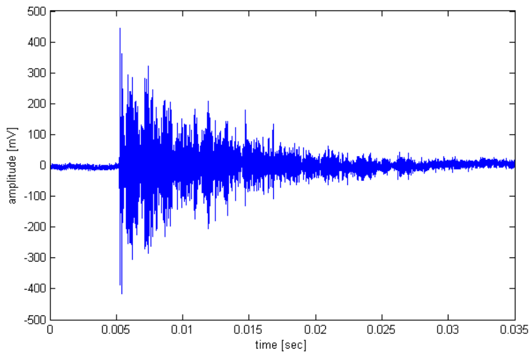

Fig. 4 Discrete emission due to crack formation (resonant sensor 100kHz)

2.2 Comparison of signals assessed with a resonant sensor or a broad band-sensitive sensor followed by digital filtering and amplification

The acoustic emission due to joint damage or to crack formation was assessed either with a resonant (100kHz) sensor or with a broad band-sensitive sensor. The results of simultaneous measurements of acoustic emission from probands / patients with the different sensors allows the comparison and an evaluation.

2.2.1 Lesions

Lesions are characterized by continuous acoustic emission. Fig.5 and fig.6 show the emission amplitudes of trigger threshold surpassing signals over time either assessed with a resonant sensor (100kHz; Fig.5) or with a broad band-sensitive sensor (Fig. 6).

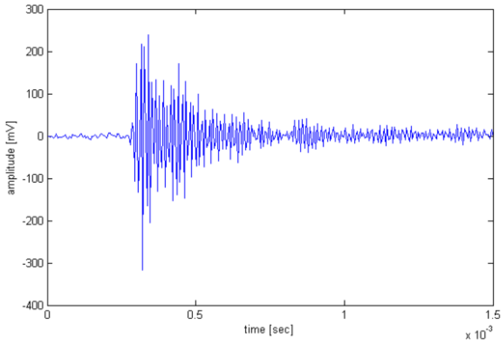

Fig. 5 Results with resonant sensor

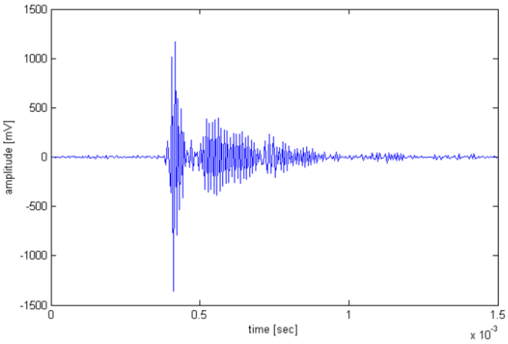

Fig. 6 Results with broad band-sensitive sensor followed by digital band pass filtering (85 kHz - 100kHz)

Both signal spectra showed high amplitudes on entering into the lesion and smaller amplitudes on sliding out of the lesion. Evidently, both sensors supplied identical signal information, whereas there were differences in details of the emission amplitudes over time.

2.2.2 Arthrosis

Joint cartilage damaged by arthrosis can lead to denudation of the subchondral bone plate and to fracture of the surfacing trabecular tips when tips of the articulating surfaces get in touch. They generate crack formation signals followed by elevated levels of continuous emission typical of friction. The latter can occur already in the phase of decline of the foregoing emission. Acoustic emission due to arthrosis is demonstrated in fig. 7 (resonant sensor; 100kHz) and fig. 8 (broad band sensitive sensor).

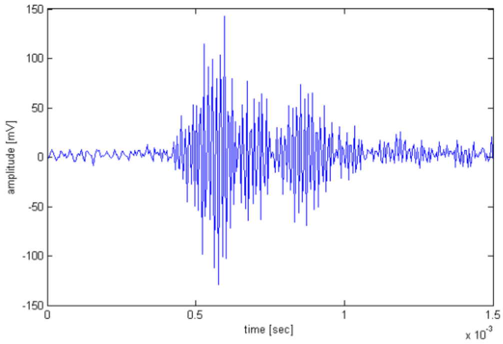

Fig. 7 Results with resonant Sensor

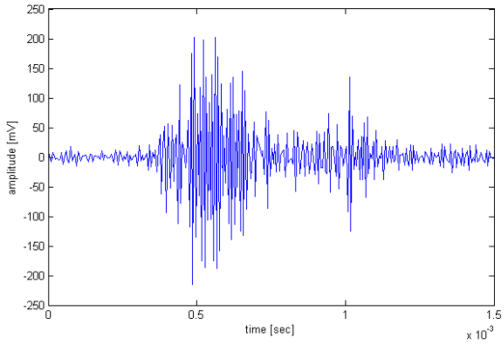

Fig. 8 Results with broad band-sensitive sensor followed by digital band pass filtering (85 – 100kHz)

Both figures reveal an initial burst typical of fracture events followed by continuous emission typical of friction between corresponding surfaces. Display of emission amplitudes over time recorded with the different sensors supplied identical information. The influence of the path taken by the acoustic emission was so far not evaluated systematically.

2.2.3 Crack formation in the femur

Crack formation in the femur is usually due to a shift in elastic moduli between compact bone and trabecular bone generating shear load in the transition region. A bone crack is a discrete event causing burst signals as acoustic emission. Usually, there is no further emission in the decline phase of a burst as shown in fig. 9 (resonant sensor; 100kHz) and in fig. 10 (broad band-sensitive sensor with digital band pass filtering; 85kHz to 100kHz). Crack formation can be followed by crack bank friction due to local relaxation.

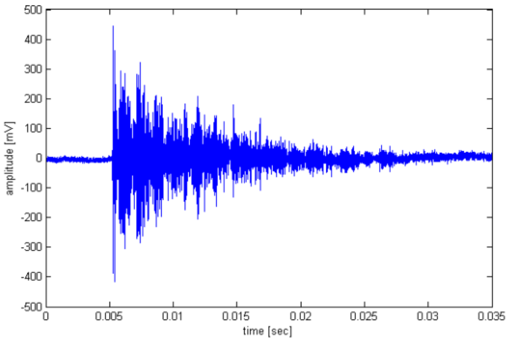

Fig. 9 Resonant Sensor

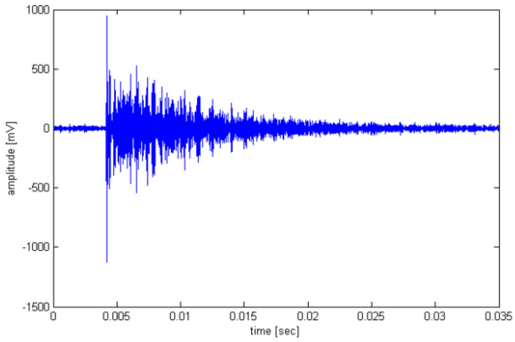

Fig. 10 Broad band-sensitive sensor followed by digital band pass filtering (85 – 100 kHz)

Simultaneous measurement with two sensors gave identical information on the burst event.

The simultaneous assessment of identical acoustic emission either with a resonant sensor or with a broad band-sensitive sensor followed by digital band pass filtering gave identical information on all relevant damage associated emission from the knee joint and from the femur. In details there were differences in the distribution of emission amplitudes over time.

That allows to assess acoustic emission due to knee joint damage or to crack formation or crack propagation with a broad band-sensitive sensor followed by digital filtering. Using a small volume, low weight sensor will considerably ameliorate the application frequency of this AE-evaluating system in the routine diagnostic.

3. Application of AEA for the optimization in the development of failure-adapted artificial femora

It would be unethical to apply AEA on arbitrary big numbers of donated human femora. Moreover, the biological human femora are individually shaped and structured and their use for the systematical examination of material properties is limited. For systematical examinations there is a need for artificial femora exhibiting a constant and identical cracking behaviour.

This approach is based on natural, healthy human femora as shown in fig. 12. From a mechanistical view the external zone (compact bone) is more or less responsible for load transfer, whereas the internal zone (trabecular bone) supplies stabilisation. The femora examined and donated from patients with osteoporosis showed rarefaction especially in the trabecular bone and also some in the compact bone (Fig. 14). The artificial bone has to be shaped and structured so, that it realistically simulates load-deformation behaviour and material strength of natural compact bone. Demonstration of geometrical similarity is not sufficient to prove the similar or same material behaviour. More importantly, the artificial bone has to show the same fracture-mechanical properties and the same failure kinetics. The first generation artificial bone made of polyurethane [4] and the donated human femora were loaded under identical conditions until cracking. The loading conditions corresponded to the natural loading conditions acting on human femora, which is a superimposition of bending and of torsional load.

The fracture image of the artificial bone (Fig. 15) corresponded to that of healthy bone (Fig. 11) and to that of the osteoporotically altered human femoral bone (Fig. 13). Clear to see was the dominant screw like torsion fracture propagating at an angle of ±45° precisely in axial direction.

Fig. 11 Fracture image of healthy human femur subjected to bending-torsional load [5]

Fig. 12 View on the structure of a healthy human femur cut perpendicularly to the axis showing compact bone in the outer zone and trabecular bone in center parts.

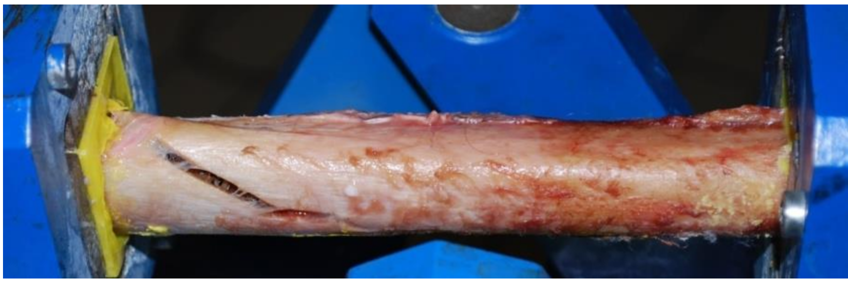

Fig. 13 Fracture image of osteoporotically alterated human femur subjected to bending- torsional load

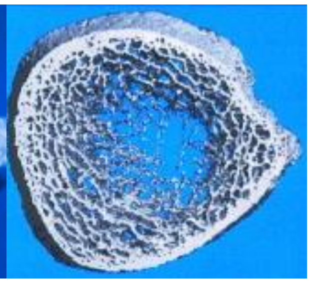

Fig. 14 View on the structure of an osteoporotically alterated human femur cut perpendicularly to the axis showing rarefied trabecular bone and some rarefaction in compact bone.

Fig. 15 Fracture image of artificial bone subjected to bending-torsional load. [4]

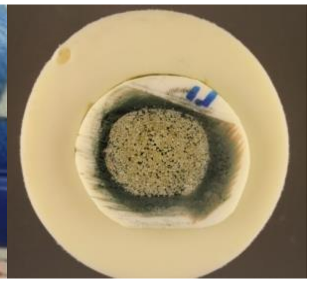

Fig. 16 View on the structure of an artificial bone showing a compact part at the outer zone and a more or less porous material in center parts. [4]

The macroscopically accessible information about the fracture behaviour seemed to indicate that it was the same in all three cases. According, however, to AEA the principle kinetic of crack formation in artificial femora differed considerably from the kinetics in both types of donated human femora, those which were healthy and those which showed signs of alteration due to osteoporosis. The applied loading conditions were identical.

Figure 17 shows the dependency of the course over time of summed up acoustic emission momenta related to the summed up momenta at the time of cracking and the material strain related to the strain at the time of cracking upon the applied load in the universal testing machine. This enables a direct comparison of the failure kinetics in all three examinations. Cracking in the donated healthy and osteoporotically altered femora started first with singularized cracks which right before the fracture could be observed macroscopically to coalesce and to release higher fracture energy (elevated sum-up of momenta per emission event). Contrary to that, AEA revealed in artificial femora a nearly constant course of failure over time starting at a low load already.

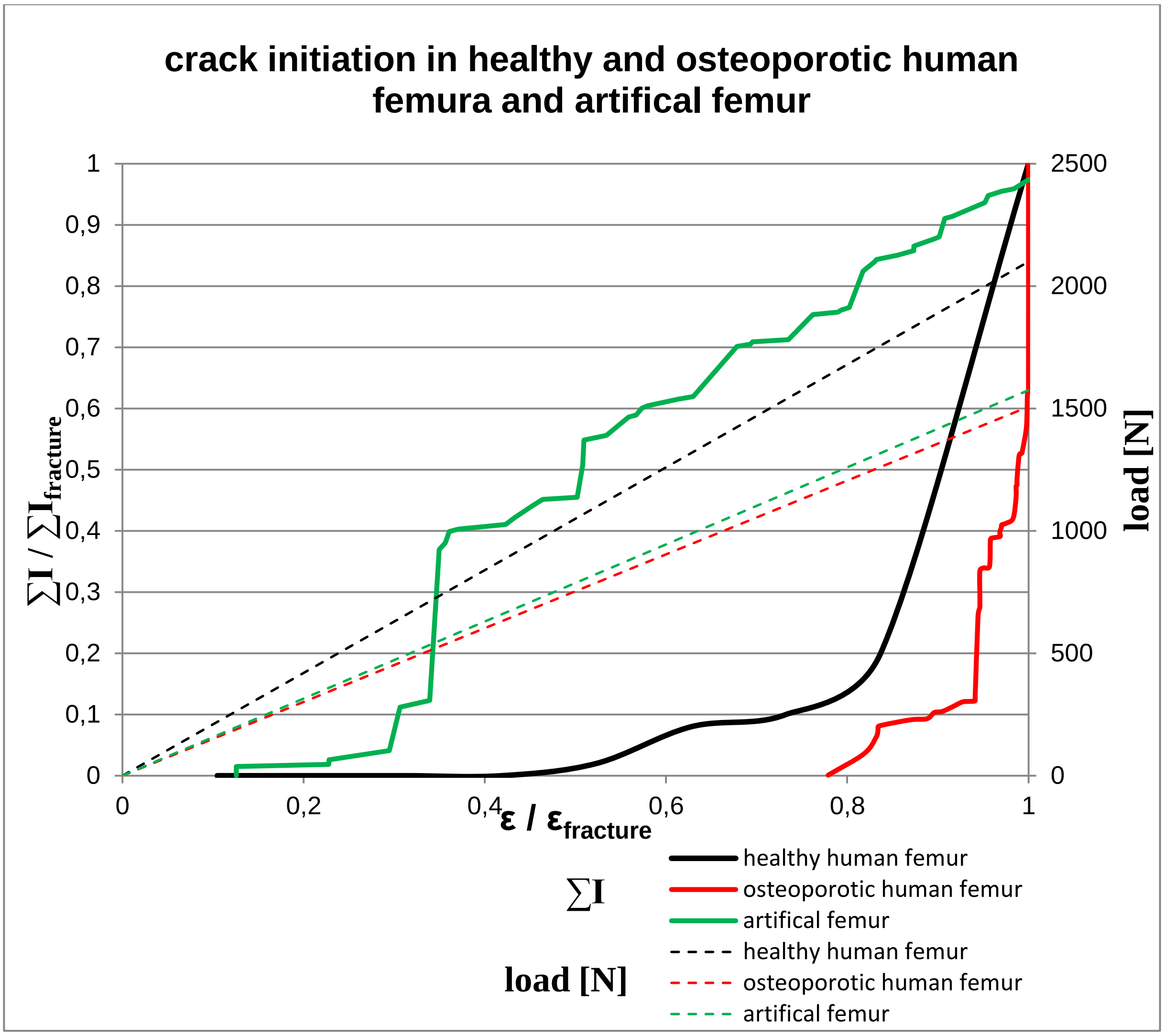

Fig. 17 Crack formation in donated healthy and osteoporotically alterated human femora and in artificial femora. [4, 5]

AEA revealed that geometrical shape and structure alone did not correspond to the failure mechanisms of natural bone. Material properties as well as the structures of compact-like and trabecular-like parts of artificial femora are thought to need adaptation to natural bone in order to mimic also the failure kinetic of natural bone.

These initial examinations [4] are a prerequisite for the optimization of artificial bone. A variation of the porous structure (simulation of trabecular bone) in central parts, of the compact peripheral parts (simulation of compact bone) and of the transitional interface between both will have to follow.

Summary

Acoustic emission analysis (AEA) is well suited to assess tribological processes in the moving knee joint under load as well as crack formation in femora under physiological load. AE of crack formation under load proved to be identical in vivo and ex vivo.

AE related information did not depend on the type of sensing sensor used. Both, the resonant sensor (100kHz) and the broad band-sensitive sensor with following digital band pass filtering worked well. The broad band sensitive sensor has a much smaller volume and can therefore be used much simpler in the medical diagnostic.

According to AEA can the fracture behaviour of human femora not be simulated with femur-shaped artificial femora representing the contemporary state of the art. While the fracture image is similar, the failure kinetic is not. The optimization of artificial bone in the next rounds of examination will follow AEA criteria.

Literature:

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