Experimental Mechanics
DOI 10.1007/s11340-012-9684-3

An Acoustic Emission Study for Monitoring Anterior Cruciate Ligament Failure Under Tension

**N.K. Paschos · D.G. Aggelis · N.-M. Barkoula ·
A. Paipetis · D. Gartzonikas · T.E. Matikas ·
A.D. Georgoulis**

Received: 26 February 2012 / Accepted: 23 September 2012

Abstract The analysis of the acoustic signals produced during anterior cruciate ligament (ACL) failure could be useful in understanding its behavior. The purpose of the present study was to evaluate the role of coupling conditions of the sensors and to determine the value of newly introduced acoustic emission (AE) parameters. Seven femur-ACL-tibia complex (FATC) specimens were fixed in a universal tensile testing machine and load was applied. Different coupling conditions were applied in two groups of specimens. The load-time curve was monitored, with the simultaneous recording of the acoustic signals and the failure mode. During ACL tear, detectable changes in the load-time curve occurred linked to changes in the macroscopic sequence of events and the measured AE parameters irrespective the coupling conditions. AE provides information on the determination of the moment (or load) when crucial irreversible damage occurs. Furthermore, specific AE indices exhibit changes throughout the testing, and imply shift of the failure mechanisms.

Keywords Anterior cruciate ligament · Acoustic emission · ACL failure · Cadaver · Knee injury · Irreversible damage

N.K. Paschos · D. Gartzonikas · A.D. Georgoulis (✉)
Department of Orthopaedic Surgery, Orthopaedic Sports Medicine Center of Ioannina, University of Ioannina,
PO Box 1186, GR-45110 Ioannina, Greece
e-mail: georgoulis@osmci.gr

D.G. Aggelis · N.-M. Barkoula · A. Paipetis · T.E. Matikas
Department of Materials Science and Engineering,
University of Ioannina,
PO Box 1186, GR-45110 Ioannina, Greece

Introduction

Despite the increasing interest for human tissue replacement, the knowledge of the dynamic mechanical properties of the human tissue is limited [1]. Although strength and elastic behavior of various tissues have been investigated, there are limited studies concerning their failure properties [2]. Understanding of the failure behavior and specifically the different failure modes is essential for the development of advanced surgical tissue replacement techniques aiming at the highest possible quality of repair.

A useful tool for monitoring failure phenomena in various materials is acoustic emission (AE). AE technique has been recently used in various engineering applications for damage characterization [3–7], evaluation of the failure process and mechanisms [6–9] and fracture location [10, 11]. Based on the recorded waves many parameters are calculated and analyzed in order to characterize the distinct failure mechanisms [12]. A typical AE signal is shown in Fig. 1. Some of its basic parameters are the arrival time (point of the first threshold crossing), the "amplitude, A" which is the voltage of the maximum peak of the waveform and "duration" which is the delay between the first and last threshold crossings. Additionally, very important is the duration of the initial (rising) part of the signal, "Rise Time", which is defined by the time delay between the first threshold crossing and the maximum peak. A frequency indicator is "average frequency, AF" which is the number of threshold crossings over the duration of the signal and is measured in kHz. The shift of the AF value during the time of the experiment, in engineering terms, is indicative of the shift of the cracking mode from tensile (early fracture) to shear (final stage) [12, 13]. On the other hand, the A of the AE

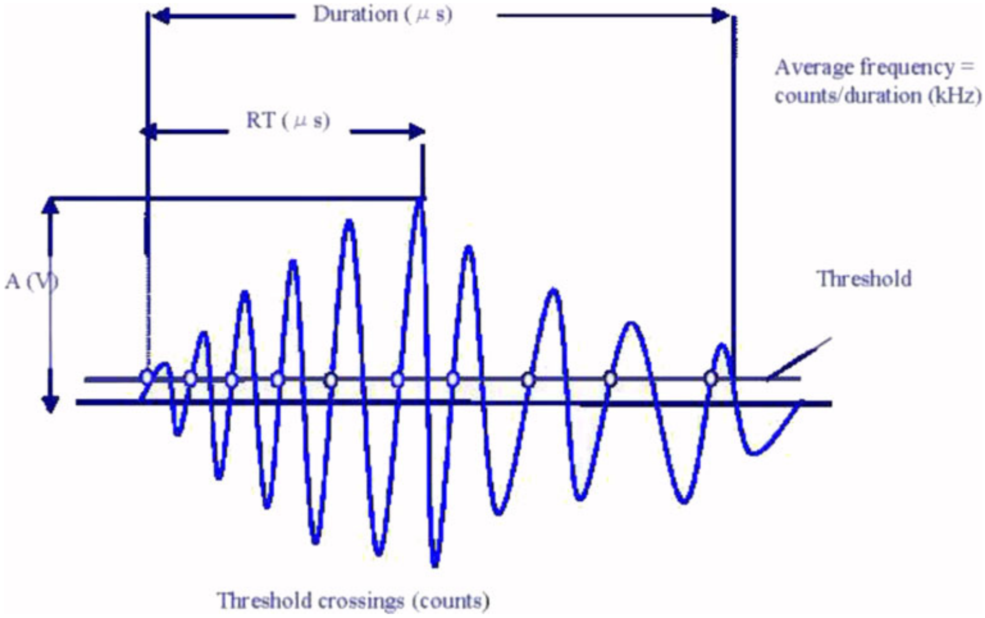

Fig. 1 Typical AE signal with major parameters (A: Amplitude, RT: Rise Time). The onset is the moment of the first threshold crossing and A, is the maximum voltage exhibited by the highest peak of the waveform. Duration is the time span in μs, between the first and the last threshold crossing. RT in μs is the time between the onset and the peak of the highest cycle. AF is calculated as the ratio of the number of threshold crossings of the waveform divided by its duration

signals is generally indicative of the energy released by a crack propagation event [14] and it depends strongly on the material's inherent attenuation (viscoelastic damping and scattering) due to its microstructure as well as accumulated damage [15].

In orthopaedics, the AE technique has been mainly applied as a predictive tool for the *in vitro* assessment of cemented implanted orthopaedic constructs [10]. The use of AE techniques has been expanded in various fields. An AE-based system was introduced in order to evaluate the risk of frontal bone fracture due to blunt impact [16]. Furthermore, AE technique has been used as a biomarker for assessment of knee joint degeneration due to osteoarthritis [17]. However, very limited studies have employed the AE technique for the stress-induced damage monitoring of soft tissues and biomaterials in the past [19–22]. Recently, a study evaluating the AE activity during anterior cruciate ligament (ACL) rupture, suggested that specific type of sensors could adequately capture the AE activity and a potential correlation between AE behavior and failure process [23]. However, the sensors were placed in a small cavity drilled into the bone, thus limiting its clinical relevance [23].

In the current study, placement and acoustic coupling conditions were evaluated. "Coupling" is referring to the conditions enabling the acoustic energy to propagate from the material under test into the transducer. The purposes of the current study are: (a) to evaluate the role of positioning of the sensors to the bone in AE activity during ACL rupture (b) to evaluate whether the newly introduced AE concepts, such as the shift of AE indices like AF, correlate with a simultaneous shift in damage modes of the ACL. The hypothesis of the study was that the position of the sensors would affect the recording of AE activity. A shift of AE indices could indicate shift of the failure process from the early stage to the final stage, similar to that observed on other engineering materials [12, 13]. This is a pilot AE study on human ACL and it is not within its scope to reproduce a physiological test of the human ACL failure.

Experimental Procedure

Seven fresh frozen human cadaveric knees with a mean age of 86.5 (range from 83 to 90 years old) were studied. The institutional review board approved the experimental process. The specimens were preserved in sealed polyethylene double bags and stored at −20 °C. A saline-soaked gauze was used to maintain specimens moisture. The specimens were thawed at room temperature 24 h before preparation and testing. All specimens were evaluated clinically for stability. All specimens had no signs of previous injury or surgery. Subsequently, all soft tissues apart from the ACL were removed, in order to reduce the acoustic signals produced by the potential failure of these soft tissues.

Each Femur-ACL-Tibia complex (FATC) was then placed in a custom manufactured clamping device and positioned at 15° of flexion. In this position, the *in situ* force distribution is equal between the anteromedial (AM) and the posterolateral (PL) bundles of the ACL [22, 24]. The positioning also ensured that the loading axis would be the axis of the ACL (Fig. 2) [22, 24]. Then, each FATC was loaded from the relaxed position up to failure at a displacement rate of 1.5 mm/s. Since the fixation of the specimen to the clamps was adequate in order to allow the alignment of the ACL with the loading axis preconditioning was not

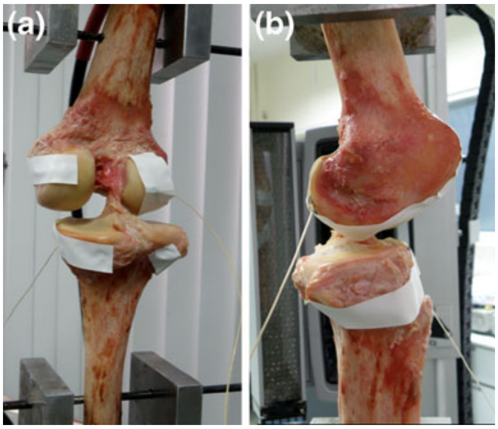

Fig. 2 Femur-ACL-Tibia complex placement in the clamping device (AP and lateral views)

applied. Furthermore, it was not within the scope of the current study to reproduce a physiological test that would necessitate the need of preconditioning. During testing, load-time curves were recorded. The decline of load to values below the 90 % of its maximum values was defined as failure of the specimen. Two high-resolution cameras were used to record the experimental process. Two experienced orthopaedic surgeons in ACL reconstruction conducted the detailed description of macroscopic events during ACL failure, as well as the report of the topography of the tear from the analysis of the recorded tapes [22].

For monitoring the AE activity two wide band AE sensors (Pico, Physical Acoustics Corp., PAC) were used. The sensors had a cylindrical shape with a height of 5 mm and a diameter of 5 mm also. Their small size enabled direct attachment to the bone without the need for specific coupling device (shoe). In four specimens (ACL1, ACL2, ACL3, ACL4) the sensors were directly attached one on the femur and one on the tibia, approximately 10 mm from the attachment of the ligament to the bone, respectively. The same technique of sensor fixation was used in all specimens. The sensors were secured with electric mounting tape, while a layer of medical ultrasonic gel was used between the sensors and the bone surface to enhance acoustic coupling [23]. In three specimens (ACL5, ACL6, ACL7) the sensors were placed at the same location. The only difference was that two small cavities (5 mm diameter and 3 mm depth) were drilled on the tibia and femur respectively (Fig. 3) [23]. In all cases, the described setting enabled the recording of the AE from the detachment of the ligament from its femoral or tibial insertion to the bone, as well as from the substance tear of the specimen, via propagation of the signals through the tissue into the bone where the sensors were placed.

The specific sensors exhibit high sensitivity to frequencies ranging from 50 kHz up to 800 kHz, with maximum sensitivity at 500 kHz. This spectral response allows recording signals from a wide range of different sources. A two channel monitoring board PCI-2, PAC was used for data acquisition, digitization and storage of the AE waveforms. A pilot test was used for the determination of the threshold. 40 dB was found to be adequate in order to diminish the risk of environmental noise interference to the emission signals. The pre-amplifier gain (1220A, PAC) was also set at 40 dB. A sampling rate of 5 MHz was selected for the recording of AE hits (including whole waveforms). The cumulative AE activity, the AF of the signals and their amplitude were the main features of the AE testing analyzed.

Results

All specimens exhibited a polytonic response during failure. The macroscopic changes observed in the video frame analysis coincided with the changes in the load-time curve. When a failure was observed macroscopically, a corresponding drop in load was shown in the load/strain curve. However, this drop of load was not complete. Additional loading resulted in further fiber failure. When another macroscopic event was seen, a drop in load accompanied this event as well. Consequently, a rupture of a group of ACL fibers caused adjacent changes in the load-time curve, and specifically produced a peak or plateau in the curve. Figure 4 summarizes the mechanical load versus time along with the cumulative AE hit curves from both sensors for all tested specimens.

From the macroscopic analysis, five of the specimens exhibited succeeding substance tears of fibers of the ligament. Three specimens from the group with holes (ACL1, ACL2 and ACL4) and two from the group without holes (ACL5 and ACL6) failed with a substance tear, located at the tibial one third of the ligament. Two specimens (ACL3 and ACL5) failed initially through an avulsion fracture of the tibial insertion of the ACL, followed by substance tears of groups of fibers. These changes were accompanied with simultaneous changes in the load/elongation curve. Analogous changes were recorded in the AE hit curve with an increase in the AE acquisition rate. Due to the sensitivity of the sensors to capture waves of the micro-scale, AE activity is sometimes recorded prior to the evident load drop and macroscopic sequence (Fig. 5).

Regarding the coupling conditions, the behavior of the two groups was qualitatively similar, with comparable patterns exhibited in general. The hits recorded in the first four specimens were approximately 230 (range from 87 to 314) in average, lower compared to the 1130 (range from 804 to 1,512) that were acquired for the second data set (specimens with sensor holes). This certainly implies that the coupling conditions were improved by the hole. Specifically, the fact that more signals are acquired when sensors are embedded is a strong indication of better transmission. Also the amplitude of

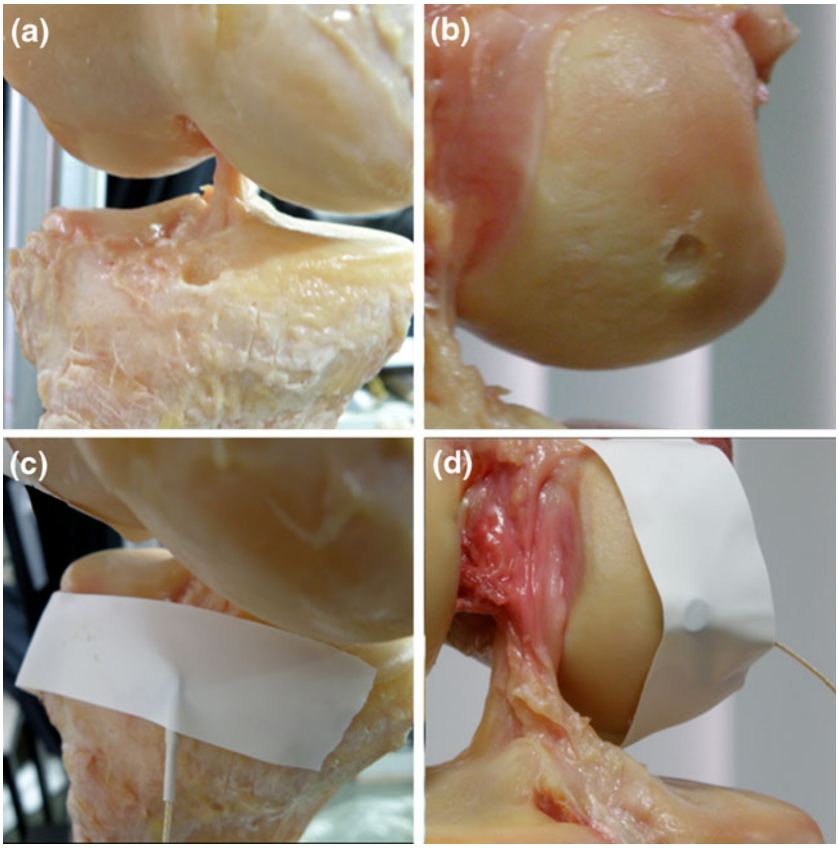

Fig. 3 Attachment of the sensors to the specimen with the support of tape. Small holes were created in the tibia and femur of the last three specimens to ensure better attachment. Example of specimen 6

the signals acquired with the cavity reaches even 70 dB, while for the surface placement reaches 60 dB, which is a notable difference. Nevertheless, a population of 230 is a considerable number of signals sharing similar time function. This finding suggests that even with simple placement of the sensor on the bone surface a sufficient population of data can be obtained for adequate analysis. Figure 6 compares the monitored activity of two coupling conditions on the example of ACL2 (without cavity) and ACL6 (with drilled cavity) specimens.

The AE started during the pre-peak period and became more intense during the ligament's plastic deformation. The AE hits continued to emerge after the maximum load was reached. However, the AE hit rate was not constant but fluctuated according to the load behavior of the different specimens. The AE generation remained high during all time periods of load decline in the load-time curve. After the failure of the specimen no significant activity was recorded in most cases.

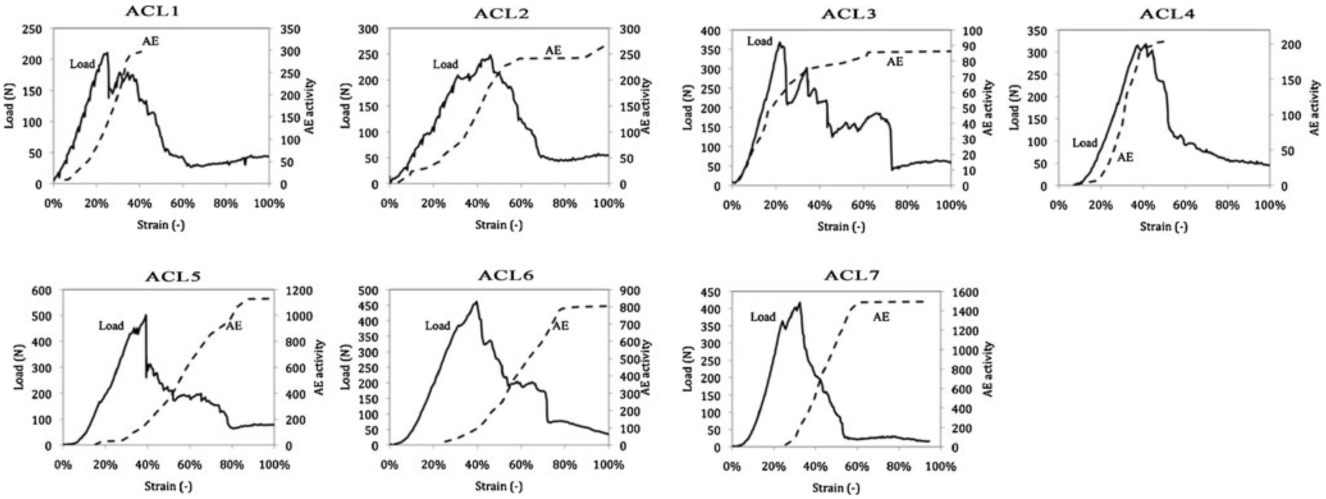

Fig. 4 Load and AE hit cumulative history for all seven specimens

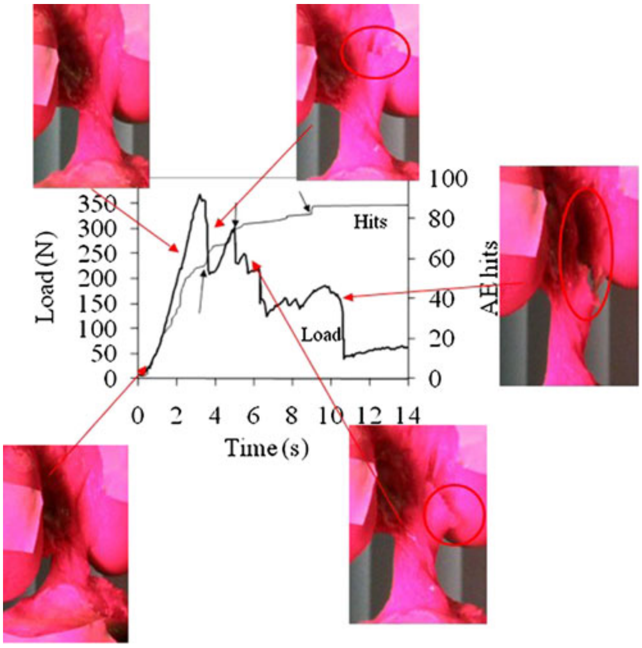

Fig. 5 The macroscopic changes observed in the video frame analysis with the coinciding changes noted in the load time and AE hit curve. Example of specimen 3

The corresponding changes of the load and the AF as a function of time are depicted in Fig. 7. The evolution of the AF curve showed a qualitative change in the nature of the events, apart from the total number of signal recordings. AF moving average line exhibited an increasing trend as the ligament underwent elongation, and despite some fluctuations reached average values much higher than the initial emissions recorded. Specifically in specimen ACL1, AF increased from less than 100 kHz to more than 300 kHz as load increased, while a smaller increase was observed for other specimens, (see ACL6 in Fig. 7).

Concerning the amplitude of the emissions, values greater than 50 dB were obtained in specimens with midsubstance fiber tear (ACL1, ACL2, ACL4, ACL6 and ACL7). On the contrary, bone avulsion in which the ACL fibers tore from their tibial attachment, gave amplitudes greater than 60 dB (ACL3 and ACL5). The moving average of the recent 40 hits for typical specimens is depicted in Fig. 8. Again, the initial emissions exhibit lower values, while in all cases, at the moment of maximum load or later, signals of higher amplitude are emitted. Note that amplitude as an AE parameter is measured in dB and therefore even seemingly slight changes on the vertical axis declare substantial actual changes in the energy of the emissions. Indicatively, an increase by 6 dB corresponds to a voltage increase of 100 %.

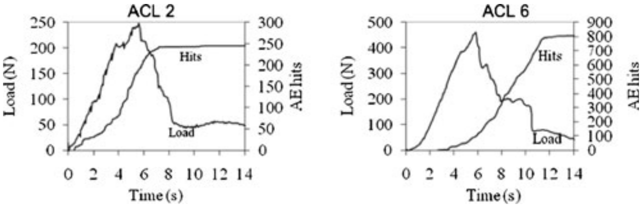

Fig. 6 Effect of sensor's placement on the AE hits—ACL2: sensor directly located on bone and ACL6: sensor placed on a cavity drilled on the bone

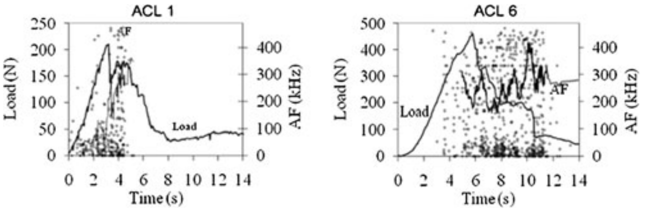

Fig. 7 Load and AF history. (The dots represent the AF of each hit, while the solid line stands for the moving average of 40 hits). Example of specimens 1 and 6

Discussion

The obtained results confirm the hypothesis, that the ACL failure is accompanied by detectable AE signals with specific properties. All specimens exhibited a non-monotonic response during loading up to failure, which is in line with previous observations [22–26]. Concerning the positioning and coupling conditions for AE measurements, it was demonstrated that placement of the sensors to the bone surface without drilling a cavity was sufficient to collect adequate AE data for the analysis, although the cavities enabled firmer contact of the sensors and better wave transmission conditions.

In terms of the AE response, the fact that during the initial deformation of the ACL, the AE hit rate was considerably low, since no permanent changes in the ACL structure occurred, is in line with previous animal studies [18, 19]. During the plastic deformation of the ACL the AE activity became more intense. This activity continued after the initial failure of the ligament. However, after this phase, no significant changes in the acoustic activity were recorded. The specimens failed at fairly low values (200–500 N), possibly due to the potential biological changes occurring to ACL with advancing age and withdrawals associated with post-mortem changes to the specimen [26, 27].

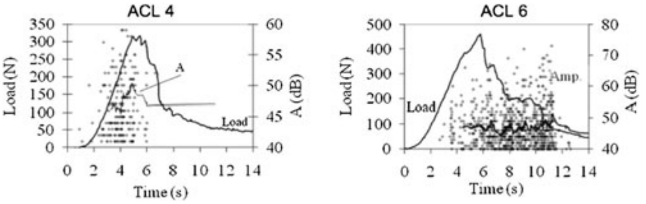

Fig. 8 Load and amplitude history. Example of specimens 4 and 6

The change of signal parameters just before macroscopic failure is not surprising. In bone applications, the concentration of AE changes in the plastic region just prior to yield has raised a concern on usefulness of this technique for clinical applications [28]. The importance of the findings of the present study was the fact that AE signals can be monitored in a material as complex and viscous as ACL, providing data for a better understanding of its behavior during failure. Also, it is important that the AE technique enables capturing even the slightest fracture incidents before they even influence load or strain measurements. In the future, this capacity could be used for manufacturing a device that could detect AE signals in the early phase of tissue deformation prior to its plastic deformation or failure. Clinical future applications include diagnostic devices for monitoring deformation phase or fatigue for injury prevention. Another future direction could be the use of acoustic monitoring in patients with a previous knee injury for detecting ACL injury.

The amplitude of the AE signals is generally indicative of the energy released by a crack propagation event [14]. As aforementioned in previous studies, high amplitude signals were recorded during fiber failure as shown in load-time curve on animal ACL [18, 19], a finding that coincided with the results for human ACL. The current results confirm previous data that indicate that bone avulsion failure produces amplitude of higher value compared to fiber failure [20]. However, amplitude strongly depends also on the material's inherent attenuation due to the microstructure as well as accumulated damage [15]. The ACL exhibits strong damping characteristics due to the viscoelastic behavior and the interactions of the collagen fibers and the matrix that reduce the amplitude of the AE signals from the point of crack propagation to the sensor. This is the reason that the amplitude of almost all the signals varied within the lower half of the available voltage range (40 to 70 dB) unlike other engineering materials tested with the same settings [13]. However, the presence of a peak of the amplitude curve at the time of maximum load, or later while the elongation continues to increase, is indicative of relatively stronger failure event occurring at that time compared to the beginning of the experiment. It should be kept in mind that after the major rupture and load drop, the decreased load is more likely carried by only a few fibers of the original tissue which therefore, are under higher stress.

The signals observed in sensors in all specimens are relatively different. This raises the question of how these differences can be interpreted and what useful information can be obtained from this method that other methods are unable to provide. However, it is hypothesized that coupling conditions may influence the shape of the received waveform, as well as the number of signals. After using both configurations (surface mounting of the sensor and mounting in a small cavity) it was obvious that the latter resulted in better coupling conditions, judging from the higher number of acquired signals. Similar approaches (with sensors mounted on the skin) are followed with reliable results in the assessment of joint degeneration due to osteoarthritis [17] although it is certain that each successive tissue layer influences the signal. In other words, the received signal may be certainly different than the emitted due to propagation through a heterogeneous and viscous medium. However, after the experimental parameters are fixed, the relative changes between specimens can be solely attributed to the material behavior excluding the possibility of scatter due to undecided experimental parameter. With fixed setup, correlations and conclusions can be reinforced and populated by more specimens.

The background of AE comes from the testing of engineering materials. The certain advantage of AE over other monitoring methods is that it enables the determination of the onset of fracture and monitoring of the subsequent stages [6, 29, 30]. It is sensitive enough to detect even microcracking that does not lead to measurable strain or load drop. In different kinds of engineering materials fracture modes can be distinguished [6, 28, 29]. However, this is one of the first pilot studies of AE on the human ACL with the reasonable disadvantage of limited experience and capability to interpret values and trends of AE indices relatively to the dominant damage mode (i.e. damage on the ligament/bone interface or fiber rupture). The interpretations and discussion may be based on similar trends exhibited by other materials, keeping of course in mind that soft tissue is certainly much different than materials typically monitored by AE.

The present study has certain limitations. The knee behaves differently when the soft tissues are removed. However, the purpose of the study was not to reproduce the axial conditions of ACL injury, but to examine its structural behavior under controlled conditions. The age of the specimens needs to be considered when interpreting the results. The low values of ultimate failure load observed are possibly due to the potential biological changes occurring to ACL with advancing age and they are in accordance with the literature [27]. The number of specimens was relatively small. Therefore, any trend observed concerning AE characteristics, cannot be a priori established as a robust correlation between AE characteristics and specific failure patterns, although it is certainly connected to the process. Additionally, in the specific case of ACL testing there is not one single failure pattern. Although it was not within the purposes of the present study, it is true that due to the small number of specimens it was difficult to detect any obvious correlation between the characteristics of the AE signals and a specific failure pattern. A certain degree of variability is expected in cadaveric specimens due to factors like age, gender, etc. Additionally, failure is a procedure strongly influenced by random parameters. Therefore, the exhibited differences were not unexpected. Concerning the testing procedure, one difficulty arises from the shape of the specimens. The geometry of the surface is irregular and not identical for different specimens, therefore preventing the attachment of the sensors on identical points in each test. This could have a differential effect on the distances between the sensors, and hence the amplitude of the signals due to different attenuation as well as cause a slight change on the coupling conditions. Another difficulty comes from the attempt to quantify accurately the fixation of the sensors. This was a pilot study; therefore its findings were limited in order to provide a safe detailed analysis of the correlation of the different AE characteristics with irreversible failure.

Conclusions

Acoustic emission was monitored during tensile failure of soft human tissue (anterior cruciate ligament) under different coupling conditions. The measured AE parameters were linked to detectable changes in the load-time curve and changes in the macroscopic sequence of events. Regardless of the coupling conditions (existence or not of sensor mounting hole), the AE behavior was qualitatively similar. The onset of the AE activity coincided with the moment of crucial irreversible damage of the ACL. AE technique could be used as a tool to enhance the understanding of the failure sequence of the ACL. AE can provide information on the determination of the moment (or the load) when crucial irreversible damage occurs highlighted by the onset of AE activity. Secondly, specific AE indices exhibit changes throughout the testing, and imply shift of the failure mechanisms, which is possible to identify after proper study. Therefore, apart from imposed challenge from the acoustic or engineering point of view, this study could provide better understanding of ACL macroscopic and biomechanical behavior during failure. While technical details should be further elaborated for future application, certain AE features, like amplitude and AF employed in the field of engineering materials seem to be sensitive enough to be employed in the AE monitoring of dynamic mechanical properties of the human tissue.

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