Rupture of anterior cruciate ligament monitored by acoustic emission

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Abstract: The scope of this study is to relate the acoustic emission (AE) during rupture of human soft tissue (anterior cruciate ligament, ACL) to the mechanisms leading to its failure. The cumulative AE activity highlights the onset of serious damage, while other parameters, show repeatable tendencies, being well correlated with the tissue's mechanical behavior. The frequency content of AE signals increases throughout the experiment, while other indices characterize between different modes of failure. Results of this preliminary study show that AE can shed light into the failure process of this tissue, and provide useful data on the ACL reconstruction.

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1. Introduction

Acoustic emission (AE) due to its passive and non-invasing nature has been used to monitor the fracture of different materials and supply information on the mechanisms leading to ultimate failure. In general, one parameter used to correlate with damage process is the cumulative AE activity, which is connected to the number of active sources. Additionally amplitude or energy parameters are connected to the energy released during each crack propagation incidence and, therefore, the severity of the source. Finally, frequency and other qualitative waveform parameters have been shown to be indicative of the fracture mode.[1–3] The above studies, among others, have been conducted mostly on engineering materials; however, the usefulness of AE has been demonstrated in certain cases of biological materials like tissues or bones.[4–6] AE enhances the understanding of the fracture mechanisms of materials with engineering significance, something crucial for construction and repair purposes. The motive for biological tissues monitoring and specifically the anterior cruciate ligament (ACL) is similar. Better understanding of the failure mechanisms of the ACL would provide significant information about its structural properties, triggering the improvement of ACL

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reconstruction techniques. The reconstruction of ACL is a casual surgical operation especially in the field of sports medicine, where knee injuries are relatively common.[7] ACL represents one of the four major ligaments of the knee joint. It mainly consists of two different bundles, the anteromedial and the posterolateral, which play a distinctive role in knee joint stability.[8] *In vitro* studies of the structural properties of the ACL demonstrated the influence of age and load orientation to ACL failure process. During ACL failure, certain macroscopic modes of failure have been observed both in clinical and cadaveric studies.[9] The most frequent failure patterns are an avulsion of the attachment of the ligament from the bone as well as a substance tear of the ligament. Recently, it was proposed that ACL is behaving as a multifiber construction during its elongation and its consequent failure.[10] Regardless of the failure patterns, it seems that during failure some fibers sustain a tear initially, while others have a remaining load potential.

In the present study, three samples of ACL were loaded in tension until final failure, with concurrent monitoring of their acoustic activity. To the authors' knowledge this is the first reported study of AE during failure of human ACL.

2. Experimental

Three fresh frozen human cadaveric knees with an age range from 83 to 90 yr 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 samples were thawed at room temperature for 24 h before preparation and testing. All soft tissues except of the ACL were removed. Each Femur-ACL-Tibia complex (FATC) was then placed in a custom manufactured clamping device consisting of two clamps: one for the femur and one for the tibia.[10] A set of transverse holes was drilled through the femur and tibia, and then a set of pins was put to secure the position of the FATC.

A servo-hydraulic Instron Universal Testing Machine 8801 with maximum load ± 100 kN was used for tensile testing. A 5 kN load cell was applied with each FATC being loaded from the relaxed position up to failure at a displacement rate of 1.5 mm/s. 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. The strain was monitored by a video extensometer. It is based on the measurement of the distance between two points marked by dark color pen along the axis of the specimen. In the specific case, the points were marked on the femur and tibia above and below the ligament.

AE monitoring of human tissue includes experimental aspects and problems, the solution of which is not straightforward. One is the severe attenuation of tissue or bone material,[11] which certainly reduces the amplitude of any propagating stress wave and, depending on the distance between the AE source and the sensors location, may hinder acquisition of meaningful signals. Another important issue is the acoustic coupling which depends on the geometry and the surface texture of the specimens. In the specific case, attachment directly on the ligament was not possible due to its short length (approximately 25 mm). It was deemed necessary to place the sensors on the bones on either side of the ACL, namely femur and tibia. Preliminary experiments conducted using tape to secure the sensors on the untreated bone surface, despite the surface curvature of the bones, revealed that the coupling was adequate to acquire hundreds of hits during the experiment duration of less than 20 s. Consequently, in order to attach the sensors in a more steady way and enhance coupling, two small cavities (diameter 5 mm and depth approximately 3 mm) were drilled on the bones and the sensors were mounted inside, securing them again with tape [Fig. 1(a)]. A layer of medical ultrasonic gel was used to enhance acoustic coupling. The type of the two sensors was Pico, PAC and their small size and weight was suitable for this kind of testing. Their frequency response allows capturing of signals in a broad band between 50 and 800 kHz. The acquisition was conducted with a sampling rate of 5 MHz in a two-channel monitoring board PCI-2, PAC.

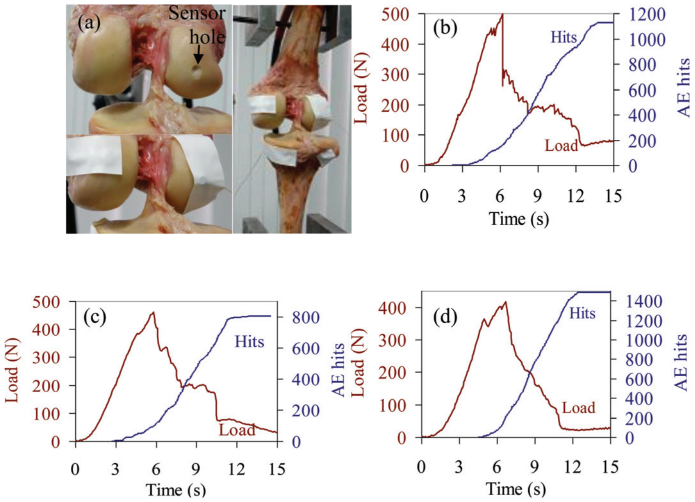

Fig. 1. (Color online) (a) Experimental set up (sensor hole, sensor secured, and whole specimen) and (b) to (d) cumulative AE activity and load history for the three ACL specimens.

The threshold was set to 40 dB in order to avoid the possibility of electronic/environmental noise and the pre-amplifier gain was 40 dB.

3. Results

Figures 1(b)–1(d) show the cumulative AE activity along with the load for all three specimens. The maximum load ranges between 400 and 500 N, while the multi-peak load behavior exhibited by some of the specimens is common for similar tissues due to the fiber nature of the ligament.[10] After the maximum load has been reached, it is certain that a main bundle of tissue fibers is ruptured; however, due to the plasticity of the material the load does not drop to zero and the elongation increases. AE starts when the load reaches 47%–84% of the maximum load in all three specimens. For a few seconds after the start of the AE activity, the slope of the AE line increases until reaching an approximately constant slope. AE continues to be recorded with the same rate until the load drops to about 10% of the maximum (much below 100 N). This shows that the failure of the ligament is gradual, behavior which is attributed to its ductile and fiber nature; the different bundles fail successively providing the irregular curve on the load history and emitting AE hits much later than the maximum recorded load. The fact that a large part of the AE activity is recorded after the maximum load is related to the ductile nature of the material while it has also been observed in fiber reinforced concrete.[13]

Apart from the level of AE activity, which shows the onset of fracture and enables the monitoring of the whole process, certain qualitative AE parameters, as mentioned in the introduction, are sought for in order to correlate with the actual failure mechanisms. In the specific study, the frequency of the AE waveforms showed a consistently increasing behavior with time, as depicted in Figs. 2(a)–2(c). Each dot stands for the central frequency of the spectrum of the corresponding AE signal. In the same figures the strain history is depicted, the rate of which was kept constant throughout the experiment. Before discussing the specific frequency trend, AE activity which starts at 3–4 s, shows that serious irreversible damage within the ligament start to occur at strains of 25% (5.7–6.7 mm for any specimen). This damage includes fiber rupture, delamination between fiber bundles, as well as detachment of the ligament from the bone insertion.[10] Stretching of the tissue does not stop even after the drop of load. It is characteristic that after the termination of the experiment, the ligaments were not separated in two parts, although they suffered plastic strain higher than 100%. As to central

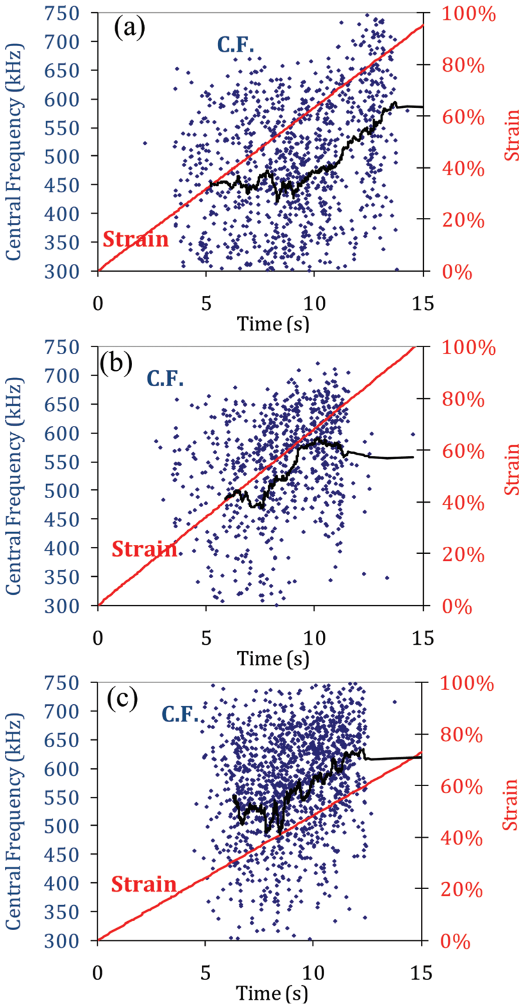

Fig. 2. (Color online) (a) to (c) Central frequency (CF) and strain history for the three ACL specimens.

frequency, which is also depicted in Figs. 2(a)–2(c), at early loading stages (before 6 s) the population of points covers the area between 300 and 600 kHz, while the cloud of points shifts to higher values as the strain continues to increase until after 12 s. At the final stages, activity is also observed at frequencies around 700 kHz, while signals below 400 kHz become less frequent. The solid line is the sliding average of the recent 50 points. The average line shows an increase throughout the duration of the experiment from around 400–500 kHz to a level higher than 600 kHz in all cases.

The frequency of each AE hit attributed to fiber failure may be connected to the stress of the fiber at the moment of rupture. The initial ruptures correspond to the stress resulting from distribution of the load on the whole number of fibers. As successive bundles are ruptured, the load is re-distributed to the remaining ones with load bearing capacity; therefore, although macroscopically the load readings drop, the fibers undertaking this remaining load are fewer and, therefore, suffer higher stress. This is a reasonable explanation for the increasing AE central frequency which correlates well with the macroscopic elongation of the ligament similar to the increase of frequency of the fundamental mode of a string when it is stretched; the sudden excitation due to fiber rupture will emit most of the energy in the fundamental mode which will exhibit higher frequency as the stress of the fibers increases.

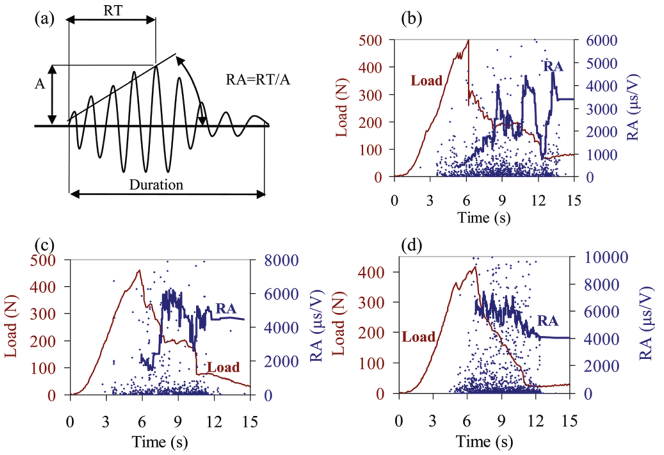

Fig. 3. (Color online) (a) Typical waveform and some basic parameters and (b) to (d) RA value and load history for the three ACL specimens.

As mentioned in the Introduction, qualitative indices of AE, resulting from the shape of the acquired waveform are studied in relation to the fracture mode of different materials. In the field of engineering materials, several indices have been established showing good correlation to the fracture mode.[12,13] One of them (RA, Rise time/Amplitude) quantifies the shape of the initial part of the waveform, as a measure of its "rising angle."[3,14] Specifically it is calculated as the rise time (RT) of the signal over its amplitude and is measured in μs/V [see Fig. 3(a)]. It has been shown that the increase of RA during a fracture process is a result of the shift of failure mechanisms from tensile cracking to fiber pull-out[13] or delaminations[14] for certain engineering materials. This is attributed to the different wave modes excited from the motion of the crack sides.[15] In the field of bio-materials the experience is extremely limited for robust conclusions concerning failure based on such AE indices. However, presentation of certain experimental trends should be discussed in order to shed light to the complicated fracturing behavior of the ACL. Figures 3(b)–3(d) show the RA value history for the three specimens. Again the dots stand for the RA of each signal and the solid line is the moving average of the 50 recent hits. For two specimens [Figs. 3(b) and 3(c)], the RA moving average line starts at low levels (below 1000 μs/V) but increases as the elongation of the tissue continues, reaching at some point values around or higher than 5000 μs/V. On the other hand, the third specimen exhibits different behavior with the RA value decreasing during the experiment, with noticeable fluctuations as well. These trends are the result of the fracture process in each specimen. The behavior, however, is not repeatable for all specimens, which is another difficulty in testing of bio-materials, in comparison to casual engineering materials that exhibit a more predictable behavior. Apart from the quantitative information obtained from the number of AE hits, the complicated fracture behavior of ACL renders the evaluation of advanced AE indices case-specific, since there is no repeatability on the original rupturing behavior which is the trigger for AE.[10] Specifically, the fracture might start from fiber rupture due to tensile load in the microscale of the fiber bundle, which could be the case for the ligaments of Figs. 3(b) and 3(c), which start with a low RA with increasing tendency. On the other hand, shear failure between bundles of fibers may trigger damage, or detachment between the ligament and the bone, which is closer to the behavior of Fig. 3(d). Therefore, the signals may exhibit much different qualitative behavior depending on the actual rupture mechanism responsible for their emission. Another parameter that was sensitive to the changes during the tensile experiment is the duration of the AE signals, the moving average of which was shown to increase, which is also connected to the shift from tensile to shear type of failure. It is again underlined that robust evaluations on the fracture mode of the ACL based on AE criteria are not possible yet, like other industrial materials. However, research should continue in this field in order to contribute more data in the discussion of the fracturing behavior of this complicated and important human tissue the repair of which is of paramount importance after knee injuries.

4. Conclusion

The present study occupies with AE monitoring of human ACL during tensile loading. Proper study of the AE behavior can shed light in the fracturing process of the tissue and specifically determine the load at which irreversible damage occurs, as well as the characterization of the failure mode which may be related to fiber bundle rupture or detachment of the ligament from the bone. The general behavior of the tissue is quite ductile while acoustic signals continue to be emitted long after the maximum load has been reached due to the failure of successive bundles. The frequency content of the signals increases steadily as the tissue is stretched, while other waveform shape parameters show certain trends throughout the experiment, implying that the shift between distinct failure modes can be identified by AE. This preliminary study hopefully contributes to the solution of experimental aspects of human tissue testing, as well as interpretation of the AE behavior which in biological materials is not much developed so far.

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