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Acoustic emissions from thoracic vertebral bodies and spinal ligaments during failure

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ABSTRACT

Tolerance data for the spine are based on failure loads in mechanical tests of cadaveric spine specimens. These failure loads are often determined using changes in slope of the force or moment response curves, a method prone to subjectivity. Acoustic emission (AE) sensors may provide more objective data on the timing of injury; these have been used to detect the time of injury of facial and ankle bones but AE signals have not been reported for spinal ligaments tested at any loading rate or for any component of the spine in dynamic loading. The objectives of this study were to 1) compare the time of injury, as determined using AE signals, to those using traditional methods (time of injury observed in high speed video for ligament specimens and time of peak load observed on a force vs. time plot for bone specimens) and 2) compare the AE signals from vertebral body and ligament specimens in terms of amplitude and frequency. Isolated cadaveric vertebral bodies (VB, n=3) and ligamentum flavum (LF, n=3) specimens from the thoracic spine were tested in compression and tension, respectively, using a servohydraulic material testing machine while collecting AE signals and high speed video at 33,057 frames per second. Time of injury was determined using the peak amplitude of the AE signals and this was compared to that determined using traditional methods (time of peak force and time of first visual evidence of injury). AE signals from VB and LF specimens were also compared in terms of peak amplitudes and frequency contents. Two VB specimens failed by fracture (the mechanism of failure could not be visualized for one specimen) and the mechanisms of failure for the LF specimens were stripping of the ligament and periosteum from the bone (laminae). Time of injury determined using AE signals produced median differences (from those defined using traditional methods) of 0.5 and 0.2 ms for VB and LF specimens, respectively. VB fractures were associated with higher amplitude and higher frequency AE signals than those associated with LF failures (median amplitude 88.3 vs. 76.7 dB and median characteristic frequency of 55 vs. 27 kHz); although in this study this difference could not be evaluated statistically. Using AE signals, identification of the time of injury and differentiation between failures of different spine components was possible. Using these sensors it may become possible to decode complex failures of the spine that involve combinations of osseous and ligamentous failure that occur at different times.

INTRODUCTION

Failure loads in mechanical testing of the spine are used to develop tolerance data. These failure loads are often determined using changes in slope of the force or moment response curves (Maiman et al. 1983; Pintar et al. 1995; Carter et al. 2002) and this method is subjective to some extent. Acoustic emission (AE) sensors could provide more objective data on the timing of injury as they record dynamic stress waves generated by the release of energy in a material, such as the initiation of a fracture or the rupture of ligaments. AE sensors have previously been used to identify failure of facial bones and tibiae (Allsop 1991; Funk et al. 2002a; Rudd et al. 2004). To our knowledge, AE signals have only been reported during slow loading of vertebral bodies (Thomas and Evans 1988; Hasegawa et al. 1993) and previous studies have reported that AE activity is rate dependent for cortical and trabecular bone (Wells and Rawlings 1985; Fischer et al. 1986). In addition, AE signals have only been recorded during low rate loading of ligaments of the canine and leporine (rabbit) knee (Wright et al. 1979; Azangwe et al. 2000). We feel that the low rate loading regime may not be representative of most *in vivo* failure modes and the applicability of low rate data to the analysis of injuries occurring during impact experiments is not established. Differences that may exist between AE signals from bone and ligament failures in the spine, in terms of amplitude and frequency, may assist in differentiating between failures of these structures in impact tests, thus furthering our understanding of spine injury mechanisms.

The goal of this study was to evaluate the effectiveness of AE signal monitoring in detecting and differentiating the time of injury of ligaments (ligamentum flavum) and vertebral bodies of the human cadaveric thoracic spine during dynamic loading. Specific objectives were to 1) compare the time of injury, as determined using AE signals, to those using traditional methods (time of injury observed in high speed video for ligament specimens and time of peak load on a force vs. time plot for bone specimens) and 2) compare the AE signals from vertebral body and ligament specimens in terms of amplitude and frequency.

METHODS

Isolated vertebral bodies (VB, n=3, T2) and ligamentum flavum specimens (LF, left or right side only, n=3, C7-T1) from three cadavers (average age 66 yrs) were potted in polymethylmethacrylate (PMMA). Two AE sensors (Nano 30, MISTRAS Group, Princeton Junction NJ) were mounted with cyanoacrylate glue to polyvinyl chloride (PVC) mounting brackets that were attached to the PMMA pots with screws (Figure 1). AE sensors were mounted cranial and caudal to the specimen. Specimens were mounted on a six-axis load cell caudally (MC3A-6-1000, Advanced Mechanical Technology) and they were connected to the actuator of a servohydraulic material testing machine (8874, Instron Corporation) cranially. An accelerometer was mounted to the actuator for inertial compensation of the Instron force (500 g, model 355B02 used with signal conditioner model 482A21, PCB Piezotronics, Depew NY). Specimens were tested in compression (VB) and tension (LF) to nominal strains of 25 and 40%, respectively, at a nominal test velocity of 0.4 m/s. AE signals were pre-amplified (40 and 60 dB for VB and LF specimens, respectively), hardware filtered (20 kHz high pass) and collected at 5 MHz. High speed video was captured with a resolution of 144 x 144 pixels at a rate of 33,057 frames per second (Phantom v9, Vision Research). Tests were also performed on specimens of rubber and polyurethane to examine the AE signals that were artifacts of the test setup (i.e. impact between mechanical components, friction, etc.). Specimen injuries were diagnosed by post-test surgical dissection and computerized tomography evaluation, both performed by a coauthor (JS) who is a spine surgeon. Direct anatomic evidence of injury was cross-referenced with mechanical indications of failure. Specimens were considered to be injured if there was mechanical evidence of failure (i.e. a negative slope was present in the force vs. deformation curve).

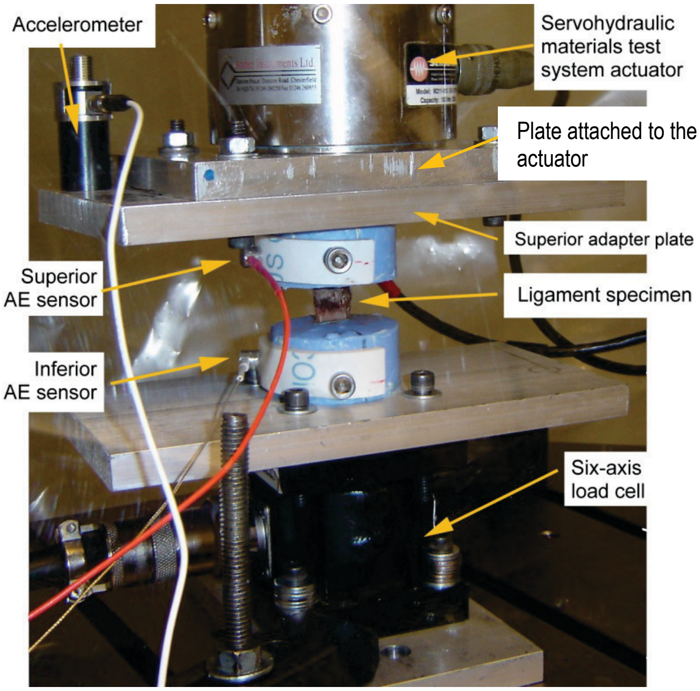


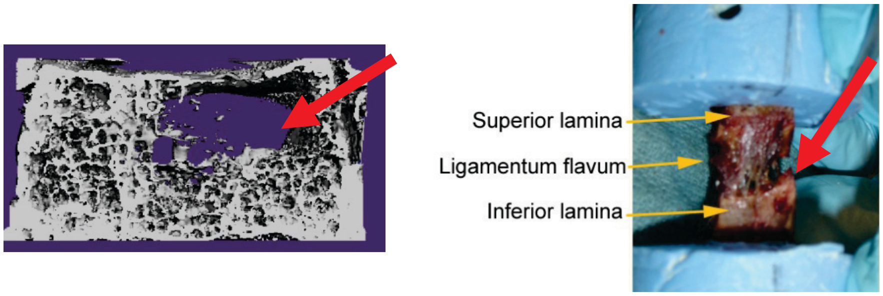
Figure 1: Photograph of the experimental test setup.

Times of injury were determined using the peak amplitude of the AE signals (first peak of the superior and inferior sensors) and these were compared to those determined using traditional methods (VB: time of peak force, LF: time of first visual evidence of injury in high speed video, as noted by one observer). The time of peak force was selected for the VB specimens as this has been previously used (Maiman et al. 1983; Shea et al. 1991; Pintar et al. 1995) and because initiation of injury was difficult to discern visually. Since the VB specimens were thicker than the LF specimens, injury likely initiated within the tissue, which would not be visible when visually examining the exterior with high speed video. The time of first visual evidence of injury in high speed video was selected for the LF specimens, as this has been previously used (Funk et al. 2002b), and because small areas of focal injury were visually observed early in the loading phase that would not be expected to result in large changes in force.

The variation of AE signals as a function of tissue (i.e. bone or ligament: VB, LF) was examined by evaluating AE signal amplitudes (in decibels, using 1 μV as a reference voltage) and frequencies. First, peak AE signal amplitudes were compared. Second, frequencies were compared by performing a continuous wavelet transformation of the signal using a Gaussian wavelet. A segment of the transformed AE signal corresponding to the time window in which the applied stress was between 80 and 100% of the maximum stress was analyzed. Characteristic frequencies of the AE signals were defined as the frequencies with the peak coefficients of the continuous wavelet transformation of the AE signal in this time window. Characteristic frequencies for the bone and ligament tissues were compared.

RESULTS

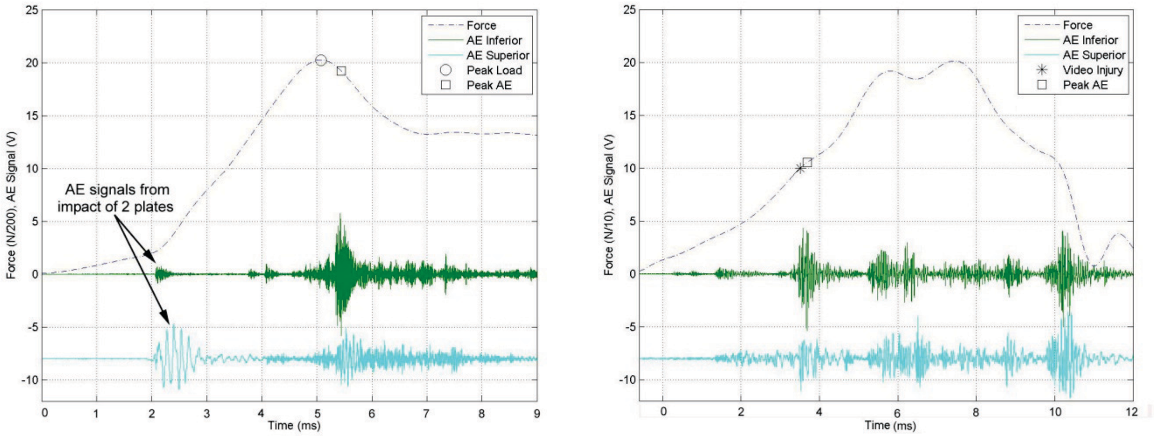
Two VB specimens failed by fracture (mid-body and under the superior endplate, Figure 2A). A fracture line could not be visualized on the exterior cortical surface for one VB specimen; however it was considered to be injured as there was mechanical evidence of failure. The LF specimens failed by periosteal stripping without evidence of bone damage (the ligament and periosteum were stripped from the bone surface, Figure 2B).



A B

Figure 2: (A) Sagittal CT image of a sample VB specimen post-testing showing a void under the superior endplate (arrow). (B) Photograph of a LF specimen post-testing showing periosteal stripping (large red arrow).

For VB specimens, AE signals were observed throughout loading with an increase in activity after the peak force was reached (Figure 3A). AE signals observed early in the loading phase were also observed for the impact tests with rubber specimens, which indicated that these were an artifact of the test setup (due to impact between the superior adapter plate and the plate attached to the actuator) (Figure 1). For LF specimens, AE signals were observed throughout loading (Figure 3B). AE signals during tests with the rubber specimens in tension were relatively low, indicating that the majority of the AE signals observed for the LF specimens were due to stress-induced changes in the specimens.



A B

Figure 3: (A) Results for a sample VB specimen. (B) Results from a sample LF specimen.

The median difference in time of injury for VB specimens, between that determined using AE signals (time of the first peak absolute AE signal) and the time of peak force, was 0.5 ms (range 0.36-0.98 ms). The median difference in time of injury for LF specimens, between that determined using AE signals and the time of injury observed in high speed video was 0.2 ms (range 0.1-1.4 ms). The time of peak AE signal always lagged the time of peak force for VB specimens.

VB fractures were generally associated with higher amplitude AE signals than LF failures (median absolute peak amplitude 88.3 (range 78.7-95.3) dB vs. 76.7 (range 63.3-82.8) dB). VB fractures were also associated with higher frequency AE signals than LF failures (median characteristic frequency 55 (range 25-278) kHz vs. 27 (range 17-36) kHz).

DISCUSSION

AE signal analysis may allow more objective and more accurate structure-specific tolerance data to be collected during impact tests. Using these sensors it may become possible to decode complex failures of the spine that involve combinations of osseous and ligamentous failure that may occur at different times (Winkelstein and Myers 1997). In this study, AE signals were recorded from isolated vertebral body and spinal ligament specimens in impact tests and peak AE amplitudes corresponded to other measures of time of injury (median difference of 0.5 and 0.2 ms for VB and LF specimens, respectively). In addition, peak AE signals were generally greater and had higher frequencies for vertebral body specimens compared to ligament specimens.

There is no gold standard for measurement of time of injury, which was a limitation of this study. However, we attempted to compare time of injury results using AE signals with traditional methods. Time of peak force was selected for VB specimens as this has been used previously (Maiman et al. 1983; Shea et al. 1991; Pintar et al. 1995) and because the initiation of injury was difficult to detect in high speed video images due to the increased thickness of these specimens. Time of injury initiation in high speed video was selected for LF specimens as this method has previously been used to identify when ligament tearing began (Funk et al. 2002b) and to classify ligament failure mechanisms (Paschos et al. 2010).

Using AE signals, identification of the time of injury and differentiation between failures of different spine components was possible.

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