

## Acoustic Emission Signals from Injuries of Three-Vertebra Specimens

Carolyn Van Toen, John Street, Thomas R. Oxland, Peter A. Crompton

**Abstract** Although acoustic emission (AE) signals from isolated spinal ligament failures have lower amplitudes and frequencies than those from vertebral body fractures, it is not known if AE signals could be used to differentiate between injured structures in spine segment testing. The objectives of this study were to evaluate differences in AE signal amplitudes and frequencies resulting from injuries of various tissue types, tested as part of a spine segment, during dynamic loading. Three-vertebra specimens from the human cadaver cervical spine were tested in dynamic eccentric axial compression with lateral eccentricities. Specimens were tested with low (n=6) and high (n=5) initial eccentricities of 5 and 150% of the lateral diameter of the vertebral body, respectively. AE signals were recorded using two sensors. The time of injury initiation was identified for seven vertebral body and/or endplate fractures and five intertransverse and/or facet capsule ruptures. Hard tissue injuries resulted in higher peak amplitude AE signals than soft tissue injuries. Characteristic frequencies of AE signals from the sensor on the concave side of the lateral bend from failures of hard tissues were greater than those from failure of soft tissues. These findings suggest that AE signals can assist in delineating injured structures of the spine.

**Keywords** acoustic emission, experimental, ligament, spine, vertebra

### I. INTRODUCTION

Cervical spine injuries are associated with substantial personal, social and economic costs [1-5]. In order to reduce the risk of these injuries occurring, injury prevention devices, such as airbags and helmets, are designed and evaluated using spine injury tolerances [6-8]. These loads are, in part, based on failure forces and moments obtained during experiments with cadaver spine specimens which show substantial variability [9-15]. This may be due to anatomic variability between specimens and due to differences in experimental methodology, including differences in the methods of determining when a fracture has occurred.

Acoustic emission (AE) signals have been used in dynamic impact experiments to detect the time of fracture of bones of the skull, face, foot, ankle and hand [16-25]. This technique has been shown to be much more sensitive than using strain gauges in detecting fracture [26]. Characteristics of AE signals have also been used to delineate failure mechanisms of composite structures and ligaments [27-31]. For example, for canine ligaments, separation of fiber bundles was associated with lower amplitude (20-50 dB), continuous-type AE activity, while fiber breakage and bone avulsion fractures were associated with burst-type activity with amplitudes usually greater than 50 dB and 60 dB, respectively [28]. Frequency information from AE data has led to the identification of failure mechanisms of composite materials (matrix cracking, fiber fractures, debonding and pull-out) [32, 33]. In order to delineate complex failures of common spinal injuries, it would be helpful to be able to distinguish the AE signatures of various structures of the spine.

Our recent study showed that AE signals from spinal ligament failures, tested in tension, have lower amplitudes and frequencies than those from vertebral body fractures, tested in compression [34]; however, these tissues were tested in isolation and in different loading modes. It is not known if these differences in AE signals would also be present in AE signals from failures of soft and hard tissues in experiments with larger spine segments (i.e. several vertebrae with the interconnecting intervertebral discs and spinal ligaments).

The objectives of this study were to evaluate differences in AE signal amplitudes and frequencies resulting from injuries of various tissue types, tested as part of a spine segment, during dynamic lateral bending and axial compression loading. The tissue types that were selected for this initial evaluation are the vertebral body, end-

C. Van Toen is a Managing Engineer at Synaptic Analysis Group in Vancouver, BC, Canada (tel: 604-872-1788, fax: 604-608-4814, [vantoen@synapacg.com](mailto:vantoen@synapacg.com)). J. Street is a Surgeon in the Combined Neurosurgical and Orthopaedic Spine Program, T.R. Oxland is a Professor in the Department of Orthopaedics and Mechanical Engineering, P.A. Crompton is the Associate Head of Mechanical Engineering, University of British Columbia, Vancouver, BC, Canada.

plate, intertransverse ligament and facet capsule. These tissues were selected as they were most frequently injured in our experiments; they are also injured in other tolerance experiments of the cervical spine [13, 35, 36], and visualization of these injuries with high speed video was possible in our experiments.

## II. METHODS

### Specimens

The experimental methods for this study have previously been described in detail [37]. Briefly, osteoligamentous human cadaver cervical spine specimens were used. Specimens were received from both US and European tissue banks. Eleven three-vertebra specimens from the subaxial cervical spine (Table 1) were potted in polymethylmethacrylate. Wires were used for fixation of the specimens in the potting. Specimens were scanned with CT (Xtreme CT, Scanco Medical, Brüttisellen, Switzerland, isotropic resolution 246  $\mu\text{m}$ ) before and after testing. Average volumetric bone mineral density (vBMD) was calculated for each specimen using Scanco software ( $\mu\text{CT}$  Evaluation Program v6.0, Table 1). This research was approved by the University of British Columbia's Clinical Research Ethics Board.

Table 1: Summary of the specimen and donor details. 'NA' indicates that the data were not available. Average volumetric bone mineral densities of the specimens are also shown (vBMD). Specimens H1275 and H1975 were from the same donor and specimens H1298 and H1998 were from the same donor. For the specimens marked with \*, donor genders were determined using DNA (deoxyribonucleic acid) microsatellite analysis performed on donor muscle tissue.

| Low Eccentricity |       |             |                                       | High Eccentricity |       |             |                                       |
|------------------|-------|-------------|---------------------------------------|-------------------|-------|-------------|---------------------------------------|
| Specimen Number  | Level | Age, Gender | Average vBMD (mg HA/cm <sup>3</sup> ) | Specimen Number   | Level | Age, Gender | Average vBMD (mg HA/cm <sup>3</sup> ) |
| H1318            | C57   | 72, F       | 620                                   | H1125             | C46   | NA, M*      | 523                                   |
| H1323            | C35   | NA, M       | 597                                   | H1329             | C57   | NA, M*      | 566                                   |
| H1321            | C46   | 72, M       | 604                                   | H1275             | C35   | 79, M       | 599                                   |
| H1298            | C35   | 68, F       | 536                                   | H1998             | C6T1  | 68, F       | 526                                   |
| H1975            | C6T1  | 79, M       | 581                                   | H1292             | C35   | 67, M       | 580                                   |
| H1274            | C35   | 78, M       | 578                                   |                   |       |             |                                       |

### Experimental Methods

Specimens were tested in dynamic axial compression (0.5 m/s) using a servohydraulic materials test system (model 8874, Instron, Canton MA) in which the axial force was applied with a lateral eccentricity to the centreline of the specimen. In order to achieve this, rollers were placed anterior and posterior to the specimen and a fixture attached to the Instron actuator applied axial load to the specimen through the rollers (Figure 1). Specimens were randomly assigned to one of two test groups: low and high eccentricity in which eccentricities were 1% and 150% of the average lateral diameter of the superior and inferior-most vertebrae. These eccentricities were selected to represent the extremes possible in head-first impacts, based on the dimensions of the head [38], and these were within the range of those used in eccentric sagittal plane axial loading [39]. Specimens were compressed by 20% and 40% of their original height for the low and high eccentricity groups, respectively, to allow for the physiologic, non-injurious lateral bending rotation that occurred in the high eccentricity loading mode.

Two AE sensors (Nano 30, MISTRAS Group, Princeton Junction NJ) were glued to an adapter bracket that attached to the inferior potting cup. Although mounting of the sensors directly to the bones would have been ideal for measurement of signals originating from the bones and ligaments, sensors were mounted to the potting cup due to the small size of specimens and the risk of damage to the sensor. AE signals were pre-amplified (40 and 60 dB for the concave and convex sides of the lateral bend, respectively), hardware filtered (20 kHz high pass), and collected at 2.5 MHz. Different preamplifications were used as soft and hard tissue injuries, shown to exhibit lower and higher amplitude AE signals in isolated tissue testing [34], were expected on the convex and concave sides of the bend, respectively.

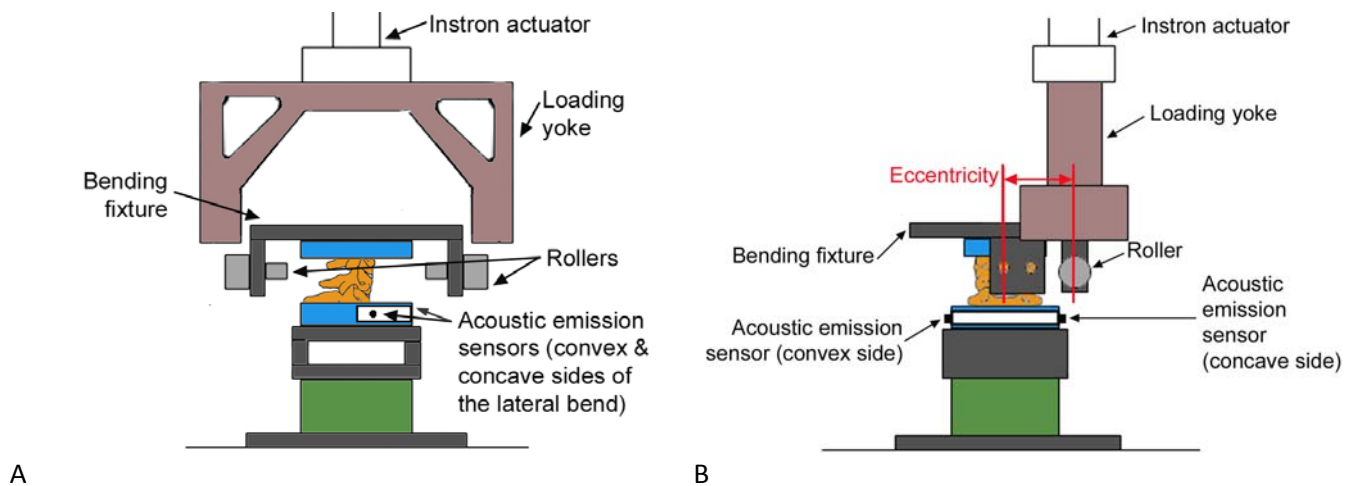


Figure 1: Schematic of the experimental test setup with key components identified: A) lateral view B) anterior view.

High-speed videos of the tests were recorded using two cameras at 6,400 frames per second (resolution 480 x 480 pixels, Phantom v9, Vision Research, Wayne NJ). These were used to identify time points corresponding to visual evidence of injury of two groups of tissue: vertebral body/endplate (hard tissue) and intertransverse ligament/facet capsule (soft tissue). These tissues were selected as they were the most frequently injured in pilot work and in the present experiments. These groups were selected due to the proximity of these structures to each other, similarity in tissue type, and because it was expected that these injuries (vertebral body and endplate or intertransverse ligament and facet capsule) would often be present for the same specimen. The times of visual evidence of injury were identified as the first frame in which visible fracturing of bone, tearing of ligaments, or sudden, rapid outward bulging or movement of part of a vertebra could be observed.

CT scans of the 11 specimens taken pre- and post-trauma were evaluated by a fellowship-trained spine surgeon (author JS). The post-trauma specimens were also subjected to careful methodical examination by the same spine surgeon. Initial injuries were diagnosed, which were then confirmed or disproved by direct anatomical visualization after meticulous surgical dissection. Anatomic components were classified as intact, partially injured (soft tissue fibers partially intact, trabecular voids present in vertebral bodies, or incomplete fracture of remaining hard tissues), or completely injured (soft tissue fibers completely torn, fractured vertebral bodies, or complete fracture of remaining hard tissues).

### Data Analysis

AE amplitudes were calculated using a reference voltage of 1  $\mu\text{V}$  and the peak amplitude in a specified time window was determined (0.5 ms duration at the time of visual evidence of injury). To examine the differences in frequency content of the AE signals from hard and soft tissues, continuous wavelet transforms (CWTs) of the signals were created using a Gaussian wavelet with four vanishing moments [34, 39]. 'Characteristic frequencies' were defined as those with peak coefficients of the CWT. Characteristic frequencies were determined for the specified time windows.

The effects of tissue (hard, soft) and sensor (convex, concave) on peak AE amplitude were examined using a multivariate analysis of variance and Student-Newman-Keuls post hoc tests. The effects of tissue and sensor on characteristic frequency were examined using Mann-Whitney U-tests and Holm's sequential Bonferroni correction for multiple comparisons. Non-parametric tests were performed on the characteristic frequencies due to non-homogeneity of variances. For all statistical analyses, a 95% level of significance was assumed (Statistica version 5.1H, StatSoft Inc., Tulsa OK).

## III. RESULTS

AE signals from one specimen in the low eccentricity group (H1975) were omitted from the analysis, as signals above the baseline noise were not recorded from the sensor on the convex side. This may have been due

to incorrect fixation of the sensor bracket on one side in this test only.

The times of visual evidence of injury (the first frame in which visible fracturing of bone, tearing of ligaments, or sudden, rapid outward bulging or movement of part of a vertebra could be observed) could be identified in high-speed video for seven vertebral body and/or endplate fractures and five intertransverse and/or facet capsule ruptures (Table 2, Figure 2, Figure 3). Where injury of more than one tissue type was observed in the same specimen, these injuries were not simultaneous, as confirmed through high-speed video. Detailed descriptions of the injuries have been previously reported [40]. Soft tissue injuries (that were visualized in all cases) were on the convex side, between the middle and inferior-most vertebrae while the vertebral body and endplate fractures were at various spinal levels and on the convex and concave sides of the lateral bend (Table 2).

Table 2: Specimens and injuries for which the times of visual evidence of injury could be identified in high speed video (VB: vertebral body, EP: endplate, ITL: intertransverse ligament, FC: facet capsule). The severity and level of injury for each test group are shown. The numbers indicate the severity of injury (1: partial injury, 2: complete injury) and the letter and number combinations indicate the level of injury (V1: superior-most vertebra, V2: middle vertebra, V3: inferior-most vertebra).

| Specimen Number                   | Test Group        | Vertebral body / Endplate |    |    | Intertransverse Ligament / Facet Capsule |     |    |
|-----------------------------------|-------------------|---------------------------|----|----|------------------------------------------|-----|----|
|                                   |                   | level                     | VB | EP | level                                    | ITL | FC |
| H1318                             | Low eccentricity  | V1                        | 2  | 2  |                                          |     |    |
| H1323                             |                   | V1                        | 2  |    |                                          |     |    |
| H1321                             |                   | V2                        | 2  | 2  |                                          |     |    |
| H1298                             |                   | V2                        | 1  | 2  |                                          |     |    |
| H1274                             |                   | V1                        | 2  |    |                                          |     |    |
| H1275                             | High eccentricity | V2                        | 2  | 2  | V2/3                                     | 2   | 2  |
| H1292                             |                   | V2,3                      |    | 2  | V2/3                                     | 1   | 2  |
| H1125                             |                   |                           |    |    | V2/3                                     | 1   | 2  |
| H1329                             |                   |                           |    |    | V2/3                                     | 2   | 2  |
| H1998                             |                   |                           |    |    | V2/3                                     | 2   | 2  |
| Total number in each injury group |                   | 7                         |    |    | 5                                        |     |    |

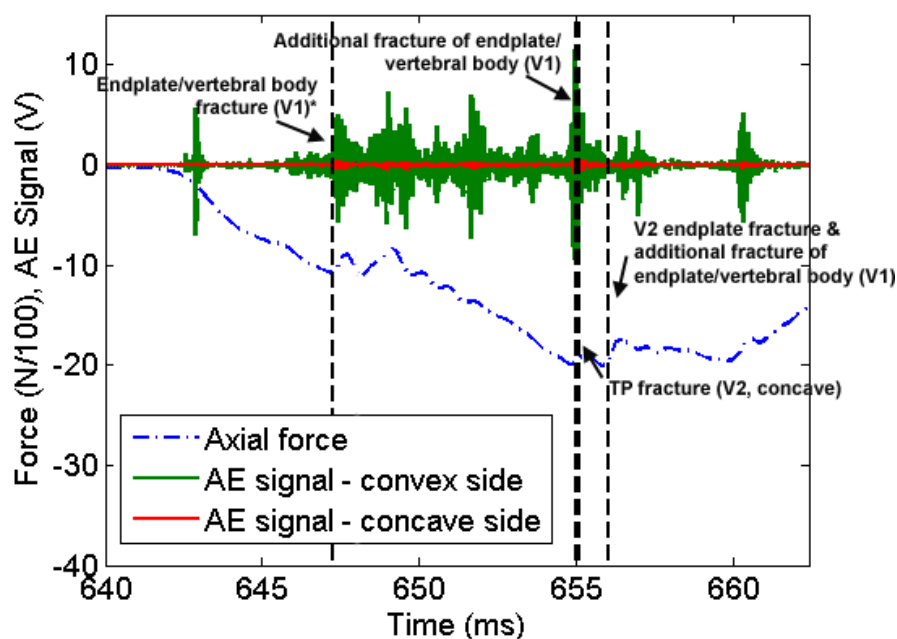


Figure 2: Axial force and acoustic emission (AE) signals versus time for a specimen from the low eccentricity group (H1318). Times of visual evidence of injury (from high-speed video) are indicated. The

time marked with an asterisk was used in the analysis (TP: transverse process, V1: superior-most vertebra, V2: middle vertebra, V3: inferior-most vertebra).

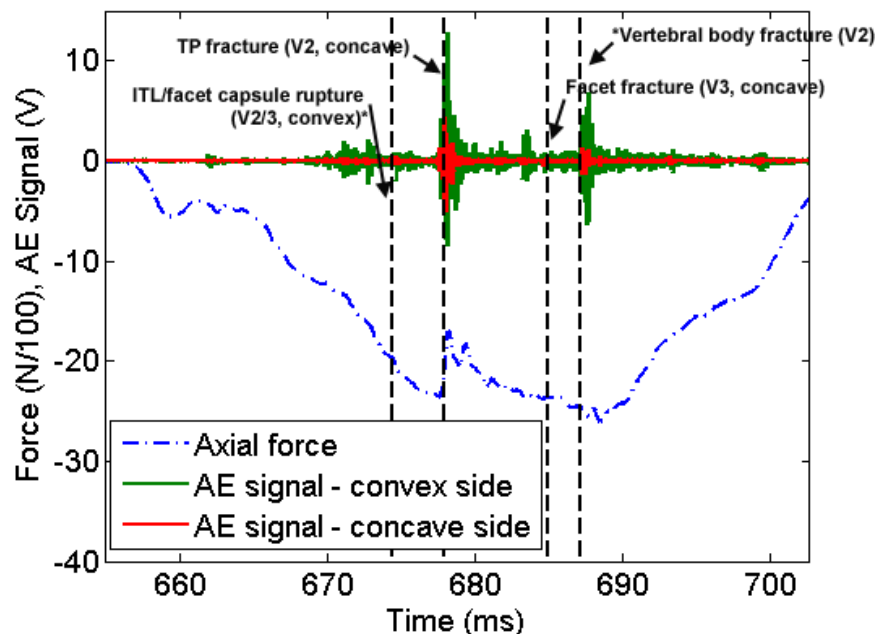


Figure 3: Axial force and acoustic emission (AE) signals versus time for a specimen from the high eccentricity group (H1275). Times of visual evidence of injury (from high speed video) are indicated. The times marked with asterisks were used in the analysis (TP: transverse process, V1: superior-most vertebra, V2: middle vertebra, V3: inferior-most vertebra).

Hard tissue injuries (endplate and/or vertebral body fractures) resulted in higher amplitude AE signals than soft tissue injuries (intertransverse ligament and/or facet capsule ruptures) (Figure 4). Peak AE amplitudes for hard tissue injuries were between 62 and 94 dB while those from soft tissue injuries were between 37 and 72 dB. There were no significant differences between signal amplitudes from the sensors on the convex and concave sides of the specimen.

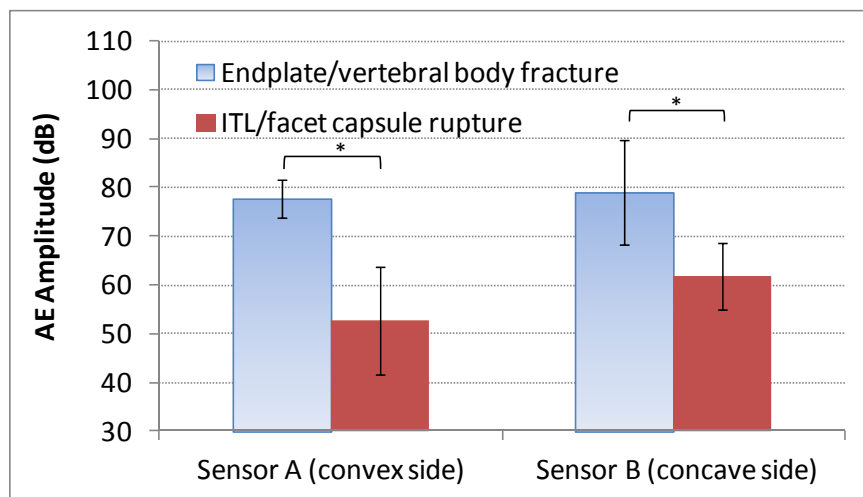


Figure 4: Average (standard deviation) peak absolute AE signal amplitudes for endplate/vertebral body fractures and intertransverse ligament (ITL)/facet capsule ruptures. Significant differences ( $p < 0.05$ ) are shown with asterisks.

Characteristic frequencies of AE signals from the sensor on the concave side of the lateral bend (with the lower preamplification) from failure of hard tissues (endplate and/or vertebral body fractures) were greater

than those from failure of soft tissues (intertransverse ligament and/or facet capsule ruptures) (Figure 5). Characteristic frequencies of AE signals from the sensor on the convex side (with the higher preamplification, from both soft and hard tissue injuries) were also significantly greater than those from soft tissue injuries from the sensor on the concave side of the lateral bend (Figure 5). Ranges of characteristic frequencies of AE signals from injuries to hard and soft tissues were 9-139 kHz and 7-25 kHz, respectively.

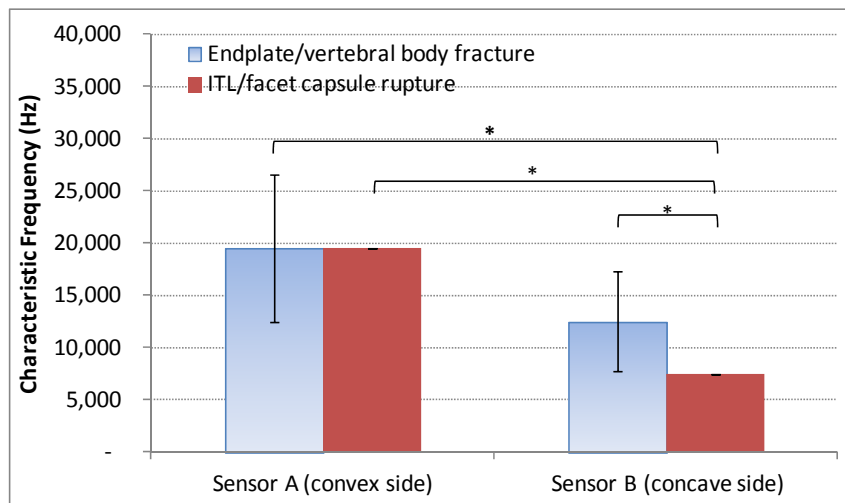


Figure 5: Median (interquartile range) characteristic frequencies of the AE signals from hard (endplate/vertebral body fracture) and soft (intertransverse ligament/facet capsule ruptures) tissue injuries. Statistically significant differences ( $p < 0.05$ ) are shown with asterisks.

#### IV. DISCUSSION

In this study, we aimed to determine if there were any detectable differences in acoustic emission (AE) signal amplitudes and frequencies resulting from injuries of various tissue types, tested as part of a spine segment during dynamic loading. Hard tissue injuries (endplate and/or vertebral body fractures) were associated with higher amplitude and frequency AE signals than soft tissue injuries (intertransverse ligament and/or facet capsule ruptures). Identification and differentiation of injured structures of the spine during dynamic experiments would be desirable in developing structure-specific tolerance data. This may be of interest as failures of some tissues may be deemed preferable, from a safety equipment design perspective. For example, isolated spinous process fractures are considered to be benign [41], while facet capsule ruptures (in combination with other injured structures) have resulted in substantial spinal cord compressions [42] and vertebral body and endplate fractures are associated with instability of the spinal column [43]. In addition, information learned using the present techniques could also be extrapolated to the clinical setting where advanced understanding of injury mechanisms could facilitate recognition of clinical injury patterns that would guide surgical treatment. For example, it may be determined that for compression-lateral bending injuries, facet capsule injuries precede fractures of the transverse process. In this instance, surgeons would then know that if there is a transverse process fracture, they should be aware that injury to the facet capsule may also be present. This may affect the way the patient is handled and treated. For instance, surgeons may want alter their surgical plan based on the structures that are likely to be injured (i.e. anterior vs. posterior approach).

The AE signals from hard and soft tissues in the current study measured on spine segments had lower amplitudes and characteristic frequencies than those measured on isolated tissues of the spine [34]. The lower signal amplitudes may have resulted from increased signal attenuation; in spine segment testing, signals had to travel through more tissue and potting material to reach the sensor. The lower characteristic frequencies may have resulted in part from the larger AE adapter bracket in the present study (half of a 10 cm diameter polyvinyl chloride tube vs. half of a 5 cm diameter tube). The frequency response of the adapter bracket would be expected to contribute to the frequencies recorded at the sensor (mounted to the bracket) and the bracket with the larger size would be expected to have lower natural frequencies [44].

For one sensor, AE signals from injuries of hard tissues had higher characteristic frequencies than those from soft tissue injuries and this is similar to findings from AE signals of vertebral body fractures and ligamentum

flavum injuries produced in isolation [34]. The two AE sensors used in the present study were in different locations (convex and concave sides of the lateral bend) and they had different preamplifications (40 and 60 dB). It is unclear if the differences in frequency observed with the sensor on the concave side of the lateral bend were due to its location (further from the soft tissue injuries) or its lower preamplification (40 dB) and thus the lower amplitudes of signals from this sensor in voltages. Future work will be required to investigate this further. It was expected that the sensor on the concave side would better capture the signals due to fracturing of hard tissues; however, vertebral body and endplate fractures occurred on both the convex and concave sides of the lateral bend [40]. At the onset of this study, it was not clear which preamplification should be used in order to capture AE signals for spine segment testing. The present results suggest that a preamplification of 40 dB may be sufficient to capture ligament injuries on the opposite side of the specimen from the sensor. This may be useful in future experimental studies.

Like all *ex vivo* studies of spine injury mechanics this study has limitations. AE signals from a small number of specimens and from various spinal levels were evaluated. Although geometric and structural variations exist between vertebral levels [45-46], this was necessary due to the low number of specimens available. Despite this limitation, statistically significant differences were observed. In addition, there is no gold standard for measurement of the time of injury of each structure of the spine. In this initial evaluation of the effectiveness of AE signals in spine segment testing, high-speed video was used to detect the presence and timing of injuries and this can only detect injuries occurring on the surface of the specimen. We feel that this speaks to the need to develop additional techniques, such as AE. Also, differences exist between the structures and mechanical properties of the grouped tissues in this study [47-48]. Therefore, it is likely that AE signals resulting from failures of these tissues may have different characteristics and these were not accounted for in this study. This was necessary due to the complexity of the injuries produced. In future studies, in order to evaluate differences in AE frequency characteristics between various anatomical structures of the spine, it may be advantageous to isolate failures of each tissue type to characterize the signatures of a greater variety of tissues. This information could then be used to deconstruct the injuries occurring in multiple level segments.

Based on the present results, it would be challenging to definitively conclude what type of tissue has failed, based solely on AE signal amplitudes alone in test series using different loading modes. For example, using signal amplitudes alone in a different study, it would not be possible to determine if a signal with a medium level of amplitude resulted from a soft tissue injury or from some response of a hard tissue (i.e. friction or micro-cracking) that was not directly associated with macroscopic injury. Using characteristic frequencies, based on the present results, differences may or may not be observed between tissue types depending on the position of the AE sensor. Future characterization of the frequencies associated with failure of various structures of the spine is also necessary to allow future advances of this technique. The present AE signal characteristics are expected to be applicable to future experiments using cervical spine specimens tested in the same configuration as those in the present study. It is a limitation that the sensitivity of the AE signal characteristics to the placement of the sensors relative to the specimens and/or injuries was not evaluated. However, our results here and our previous work with isolated segments suggest that it is a priority for good AE data to place the sensor in close proximity and to have an intimate connection between the object where the sensor is mounted and the vertebra under study. We were able to accomplish this in the present study. Additional complexities would also arise in experiments in different loading modes (i.e. tension, flexion, extension, axial rotation) and with failures of different hard and soft tissues (i.e. intervertebral disc, anterior longitudinal ligament, transverse process fractures).

The differences that we have shown in the present study and in a previous study using isolated vertebral body and ligamentum flavum specimens [34] indicate that AE signals have the potential to detect and differentiate between injuries of different tissues in the spine. Differentiation between additional tissues in the spine may also be possible (i.e. facet joints, intervertebral discs, laminae, spinous processes, anterior and posterior longitudinal ligaments). However, many more specimens would need to be tested in order to characterize the AE signatures of these tissues. As differences in AE signal characteristics may be complex, advanced signal analysis techniques would also likely be needed, such as feature extraction methods based on wavelet decompositions, such as those used for analysis of electroencephalography (EEG) signals [49].

## V. CONCLUSIONS

In this study, we have shown that endplate and/or vertebral body fractures result in higher amplitude and frequency AE signals than those resulting from intertransverse ligament and/or facet capsule ruptures. Differences between AE signals from injuries of different tissue types during dynamic experiments are of interest for delineating the initiation and progression of complex injuries of the spine to inform those developing injury prevention and treatment strategies.

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