RESEARCH ARTICLE

Design and Fabrication of a Drop Tower Testing Apparatus to Investigate the Impact Behavior of Spinal Motion Segments

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Received: 19 January 2020 *Accepted: 10 June 2020*

Abstract

Background: The vertebral column is the second most common fracture site in individuals with high-grade osteoporosis (30–50%). Most of these fractures are caused by falls. This information reveals the importance of considering impact loading conditions of spinal motion segments, while no commercial apparatus is available for this purpose. Therefore, the goal was set to fabricate an impact testing device for the measurement of impact behavior of the biological tissues.

Methods: In the present study, first, a drop-weight impact testing apparatus was designed and fabricated to record both force and displacement at a sample rate of 100 kHz. A load cell was placed under the sample, and an accelerometer was located on the impactor. Previous devices have mostly measured the force and not the deformation. Thereafter, the effect of high axial compression load was investigated on a biological sample, i.e., the lumbar motion segment, was investigated. To this end, nine ovine segments subjected to vertical impact load were examined using the fabricated device, and the mechanical properties of the lumbar segments were extracted and later compared with quasi-static loading results.

Results: The results indicated that the specimen stiffness and failure energy in impact loading were higher than those in the quasi-static loading. In terms of the damage site, fracture mainly occurred in the body of the vertebra during impact loading; although, during quasi-static loading, the fracture took place in the endplates.

Conclusion: The present study introduces an inexpensive drop-test device capable of recording both the force and the deformation of the biological specimens when subjected to high-speed impacts. The mechanical properties of the spinal segments have also been extracted and compared with quasi-static loading results.

Level of evidence: V

Keywords: Drop-weight impact machine, Fracture, Impact loading, Spinal motion segment

Introduction

The impact test provides information about the response of material to dynamic loads, which is significant for materials with time-dependent properties, like most biological tissues. Moreover, using this test, the amount of energy a material can absorb during the sudden application of force is calculated, an important factor in the design of new resistant and energy-absorbent materials (1). Due to the time-dependent mechanical properties of viscoelastic and poroelastic materials, their response toward impact

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load is different compared with static loading. This holds especially true in instances such as falls or accidents in which a large force is applied in a short period of time (2).

The Izod and Charpy impact test machines are commonly employed impact test setups. In the Izod test, a swinging pendulum hits a notched test sample firmly tied to a clamp at its lowest point of movement, causing it to lose part of its swing energy by breaking the sample. In this test, the amount of energy absorbed by the sample during fracture is calculated from the difference between the initial release and the final height of the pendulum (1, 3). Similar to the Izod test, the Charpy test consists of a swinging pendulum. The only difference is that the notched sample is hit by the pendulum in a three-point bending configuration. One of the disadvantages of the Izod and Charpy tests is generally assuming the presence of a notch in the sample, which is not an appropriate assumption for the composite material testing. Another limitation of both tests is that they are destructive and cause damage to the sample (4, 5).

Another method for impact testing is the drop-weight test, in which a given weight is released from a specific height onto a flat un-notched sample. Compared to other impact tests, this test better simulates the natural conditions of biological materials, and is thus closer to reality (1). To control the impact loads on small biological samples, Burgin et al. designed a drop tower device and used it to measure the mechanical properties of articular cartilage under impact loading. In this device, the severity of impact was controlled using impactors of different weights and different drop heights. Force and acceleration were recorded at a 50 KHz sampling rate by the force transducer placed under the sample, and an accelerometer mounted on the impactor (6, 7). Likewise, Lee et al. investigated the impact test on biological materials by fabricating a simple drop-weight test apparatus. The maximum drop height for the apparatus was 0.74 m, and the loading weight was 1.2 kg, and only the fracture energy could be determined (1).

Given the significance of vertebral column fractures, which are the second most common types of fractures in individuals with high-grade osteoporosis, several drop-weight devices have been introduced to determine lumbar segment behavior against the impact loads (8, 9). Dudli et al. applied vertical loads on several lumbar and thoracic segments of the white New Zealand rabbit by releasing a metallic sphere from a specific height. Then, the absorbed energy was calculated considering the amount of release and return heights upon impact. Based on the results, an increase in the drop height increased the energy absorption of the segment, whereas, an increase in the impactor weight increased both the energy absorption and the fracture frequency. Since this device only possessed a load cell, the change in tissue deformation was not reported (10, 11). Besides, several L1-L3 segments taken from five men and 14 women aged 62-85 years were placed in a swing pendulum impact test machine. Upon considering Kelvin's model, the dynamic stiffness and damping coefficient of the lumbar segments were calculated. The segments were first tested with no-axial preload and the stiffness and damping of the L1-L3 segment under impact loading were $135.3\pm 127.6\,{}^{kN}/_{m}$ and $372.2 \pm 121.4\,{}^{Ns}/_{m}$, respectively. Then, the tests were repeated for the compressive preloads of 30, 79 and 112 N, where the results indicated an increase in the stiffness coefficient of the segment, but no significant change in its damping coefficient (12). Likewise, Kasra et al. showed that as the preload increases, the stiffness increases due to the involvement of the posterior elements (13).

In a recent study, a drop-weight device was used in which the force and displacement were measured by a load cell and a linear potentiometer, respectively (14). With this device, 24 porcine thoracic segments (eight healthy segments, eight segments of degenerated discs, and eight segments of repaired discs) underwent impact loading. Upon comparing these three groups, the research team concluded that a significant difference was present between the maximum axial stress of the healthy and degenerated discs. The samples underwent an impact load of 1200 N, and the duration of the impact was lengthened to 20 ms with the help of a shock absorber to make it longer than the real impact duration (14).

Impact test machines that have been previously used to apply impact load on biological tissues have had certain limitations. For example, in Izod and Charpy machines, the samples must be notched, and only the failure energy can be calculated (4, 5). The main limitation in most drop weight type impact test devices is that they only have one load cell; thus, only the force data can be recorded, and the mechanical behavior of the biological tissue cannot be thoroughly examined (10, 11). Some devices have been designed in a manner in which the duration of impact is longer than normal, and that may not represent a real biological condition (14). Therefore, to overcome the main limitation of previous studies, first, a drop-weight impact testing device was designed and fabricated in which both the load and deformation of the sample could be accurately measured (the proposed device does not require a notch on the sample, overcoming the Izod and Charpy test limitation). Then, the fabricated device was utilized to measure the mechanical behavior of nine ovine lumbar segments under high rate compressive loads, and the results were compared to that of the quasi-static test.

Materials and Methods

Design and construction

Initially, a drop-weight impact testing machine was designed and fabricated to perform the impact tests [Figure 1]. The machine consisted of two vertical 316L stainless steel bars of 1.3 m height and 30 mm diameter mounted on a heavy baseplate of AISI 4140 alloy steel of 300 mm diameter and 50 mm thickness. The height of the bars was considered in a manner that would allow the application of a maximum impact velocity of about 4.5 m/s. The device also included a 316L stainless steel flat impactor plate weighing 5.2 kg and of 260×150×6 mm dimension that moved along the two guide rods of the device with the help of two linear ball bearings. By altering the height of the impactor in the device, impacts with different velocities and energies could be applied to the samples.

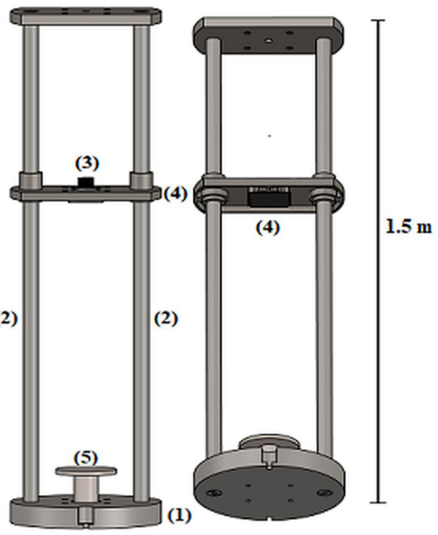

Figure 1. Schematic diagram of the drop-weight impact apparatus: 1. Baseplate, 2. Guide rods, 3. Accelerometer, 4. Impactor, 5. Load cell.

To measure the impact force, a piezoelectric force transducer (9331B, Kistler Instruments Ltd., Switzerland) was used that could measure up to ±20 kN with a precision of one percent. Additionally, an ACX-500-KU accelerometer capable of measuring a maximum acceleration of 500g (approximately 5000 m/s^2), at a bandwidth of 17 kHz, was mounted on the impactor. Data from the accelerometer and load cell were transferred into the Lab VIEW software (NXG 3.0, National Instruments Corporation, United Kingdom) to record and display the data by a data logger at a transfer rate of 100 kHz.

In this apparatus, to apply impact load, the impactor was raised to a certain height and released to collide with the sample that was placed at the lower end of the device. By using a high-speed camera (Casio Exilim EX-ZR1000 Digital Camera, Casio Computer Co, Japan), we also measured the time and the drop height during the free fall. The acceleration of the impactor during the fall was estimated at 9.60 m/s^2, about 98% of the gravitational acceleration. Since the difference between the acceleration of the impactor during the free fall and the gravitational acceleration was negligible, the friction between the impactor and the bars was ignored. Also, five impact tests were performed on each of the three polyethylene discs of 20 mm diameter and 10 mm thickness to ensure the repeatability of the tests when impacted from different drop heights of 5, 10, 15, 20, 25, and 30 cm. The results indicated less than 10% variability indicating acceptable repeatability of the device measuring sensor systems. Equation 1 was used to calculate the energy transferred to the sample due to impact (15).

Where m is the mass of the impactor, a_i is the acceleration of the impactor during free fall, h is the drop height of the impactor, t is the duration of the impact, and $F_t(t)$ is the impact force.

$$\Delta E(t) = \frac{1}{2} m[2a_i h - (\sqrt{2a_i h} - \frac{1}{m}\int F_t(t)dt)^2]$$

Data analysis

After fabricating the machine and performing the initial tests and examining the results of acceleration-time and force-time curves, secondary peaks at two millisecond intervals were observed. Upon modeling the impactor in ABAQUS software (v6.14, Dassault Systèmes, France) and conducting modal analysis, it was observed that the natural frequency of the impactor fell in the impact frequency range, which caused resonance in the impactor during the impact test. Since the accelerometer was mounted on the impactor, the accelerometer signals could have been profoundly affected by the structural vibrations of the impactor. To resolve this issue, a new impactor of different dimensions was designed and built to minimize the effect of the vibrations in the recorded results as much as possible. Moreover, high-frequency noise on the acceleration curves coming from the accelerometer bandwidth was observed. Thus, filtering was used to reduce fluctuations in acceleration-time data. To this end, a low-pass Butterworth filter was designed in MATLAB software (R2015a, MathWorks, USA) with which the noise was greatly reduced. A similar approach has also been employed in other studies to lower the high-frequency noise in the recoded data (6, 12).

Specimen preparation

Eighteen lumbar motion segments were prepared from six slaughtered sheep. The sheep were 1.5-2 years old and weighed 30-35 kg. The specimens included an intervertebral disc along with the upper and a lower vertebra. The upper and lower vertebral bodies were cut parallel to the endplates. All surrounding muscles and ligaments were removed and only the vertebrae, the intervertebral disc, and transverse processes were kept completely intact (the transverse processes were used to keep the segment stable during the impact test), as presented in Figure 2. The segments were packaged and kept at -20 °C for about a month before performing the impact tests. Then, the segments were taken out of the freezer and placed in a refrigerator at 4 °C temperature for 8 hours. Subsequently, the segments were settled in saline solution at 20 °C for 8 hours. A similar procedure has been utilized in an earlier study (12).

Figure 2. A sample of L5-L6 ovine lumbar motion segment.

Impact test

To conduct the impact tests, nine lumbar motion segments were fixed on the base of the machine with the help of a fixture, and then the flat impactor was released from various heights (5, 10, 15, 20 cm, and so on) to investigate damage to the specimen. Each specimen was impacted several times at each height. The first impact loading was performed from a drop height of 5 cm. Then, the drop height was increased by 5 cm, and the tests were repeated. The height increase was continued until complete failure of the specimen was observed. After each experiment, the specimens were kept in the saline solution for a relaxation period of 16 minutes to prepare them for the next impact test. The same solution was sprayed on the specimens to keep them hydrated during the tests, as recommended (16).

Quasi-static test

To record the mechanical properties of the ovine segment at low rates, nine ovine lumbar motion segments underwent axial compression loading by a dynamic testing machine (Hct/25-400, 25 KN load cell with a precision of one percent of load, Zwick/Roell Co, Germany) at a rate of 0.1 $^{mm}/_{s}$. The load was increased until the specimen was damaged and the results were compared with those of impact loadings. All quasi-static and impact tests were conducted at 25 °C ambient temperature.

Results

Impact test results

First, the principle of conservation of linear momentum was applied to ensure the accuracy of the device's force and acceleration data during impact. Upon examining the results of the tests, it was observed that the principle of conservation of linear momentum was well maintained, and the maximum and average differences between the drop weight energy and the area under the force-time curve were below 8.1 and 4.7 %, respectively. Table 1 presents this comparison for all the specimens at different drop heights. Also, the abovementioned uniaxial tensile testing machine was used to calibrate and evaluate the performance of the load cell at different loading rates.

The force and acceleration data were extracted from the impact test machine. Then, the sample deformation was measured by double-integrating the acceleration data. Figure 3 illustrates the acceleration-time, force-time and displacement-time curves during the collision of the specimen when the impactor was released from the height of five centimeters. It shows that during the impact the maximum acceleration and maximum displacement were 600 $\frac{m}{s^2}$ and 1.5 mm, respectively. The duration of the impact for this sample was about five milliseconds.

By deriving the displacement-force curves of one sample at different drop heights of the impactor, it was seen that the greater the drop height, the greater the magnitude of force was. However, this trend holds true until the segment is healthy; once it is damaged, the force decreases. For example, Figure 4 demonstrates the force-displacement curves recorded at drop heights of 5, 10, 15 and 20 cm; the maximum force of this sample increases from a height of 5 to 10 and then to 15 cm, but it decreases for a drop height of 20 cm, indicating that the specimen has been damaged.

Since the segments had been separated from different lumbar regions and from several sheep, to understand the effect of the type of segment and sheep from which the segment had been extracted, one-way analysis of variance (ANOVA) was conducted on the ultimate load

Table 1. Principle of Linear Momentum for the Specimens, Determined from Two Methods, First, The Impactor Mass Multiplied by Change of Its Velocity Right Before and After Impact and Second, The Area Under force-time curve

Drop Height (cm)	$m * \Delta v$	$\int_0^t Fdt$	Differences Between Two Methods
5	7.68 ± 0.26	7.54 ± 0.36	3.64 %
10	10.68 ± 0.39	10.51 ± 0.51	4.63 %
15	12.53 ± 0.29	12.32 ± 0.73	5.26 %
20	13.62 ± 0.40	13.37 ± 0.74	5.58 %

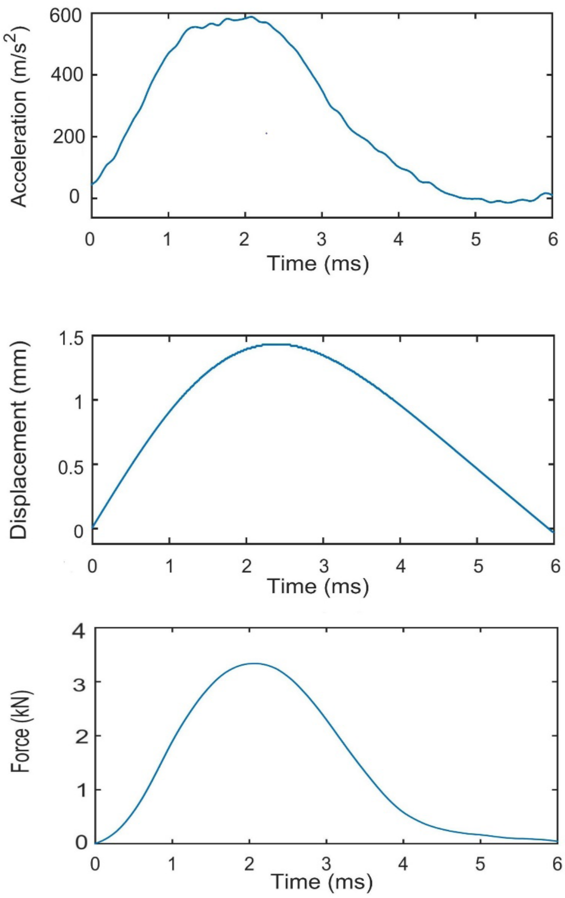

Figure 3. Acceleration-Time, Displacement-Time and Force-Time responses of a typical specimen subjected to an impact with a drop height of 5 cm.

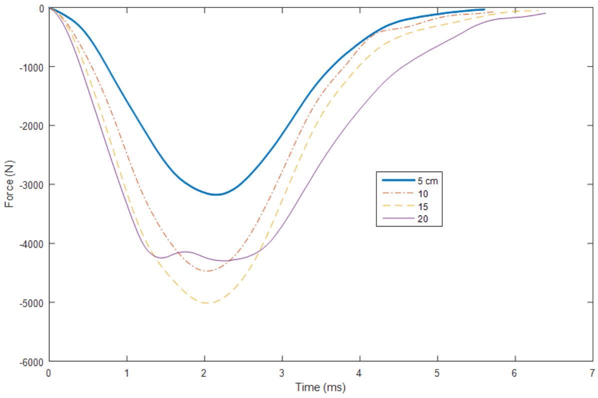

Figure 4. Force-Time responses of a typical specimen subjected to the impact with drop heights of 5, 10, 15 and 20 cm.

to failure and the maximum energy absorbed by the specimen. Based on the results, no significant statistical difference was observed between the different segments taken from one sheep (*P>0.5*), while there were significant differences between specimens taken from different sheep (*P<0.05*). The statistical analysis was performed in MATLAB software (R2015a).

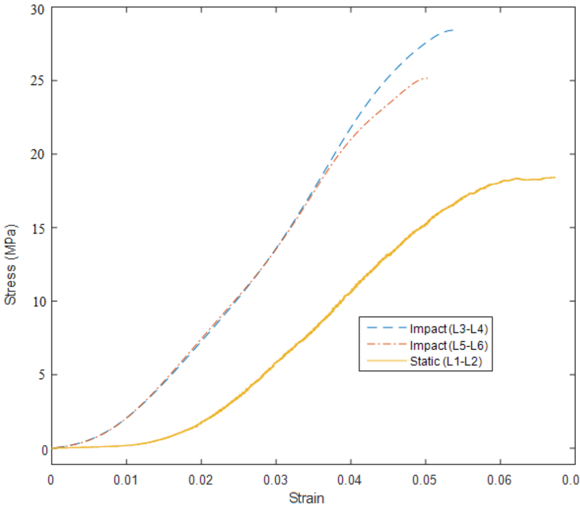

Figure 5. Comparison between results of a static loading case with two impact loading responses from the same sheep (Impact rate=2400 mm/s, Static rate=0.1 mm/s).

Comparison of the impact test and quasi-static loading results

Figure 5 presents a comparison between the segment's response to impact and that to quasi-static loading. It shows the stress-strain curve of the two lumbar segments undergoing impact when the impactor was released from a 30 cm height (some segments tolerated a drop height of 30 cm without damage), which was the maximum height at which the specimen remained undamaged. Any further increase in the drop height resulted in the damage of this specimen. Likewise, a segment that had undergone quasi-static loading until damage onset is shown. All the segments were taken from a single sheep.

The means and standard deviations of the ultimate load to failure and the failure energy of all specimens under impact and quasi-static loading have been calculated and reported in Table 2. Upon examining the segments following damage, we observed that the specimens that had undergone impact had sustained injury in the vertebral body. Fracture began in the vertebra-endplate interface in seven out of nine segments, while, the upper surface of the vertebra in contact with the impactor was damaged in the other two specimens. The vertebra was initially damaged in this region. However, for segments subjected to the quasi-static loading, the damage occurred in the endplates, a different location compared to those observed in the impact loading.

Table 2. Mechanical Properties of Specimens in Quasi-Static Loading and Impact Loadings (Average ± STD)

Parameter	Quasi-Static Loading	Impact Loading
Ultimate Load to Failure (N)	4822 ± 448	5830 ± 1588
Displacement to Failure (mm)	3.55 ± 0.34	3.38 ± 0.63
Ultimate Stress (MPa)	18 ± 0.89	19.60 ± 4.80
Strain to Failure	0.064 ± 0.006	0.059 ± 0.009
Failure Energy (J)	7.08 ± 0.39	9.41 ± 2.86

Discussion

To the best of our knowledge, few studies have been conducted on the mechanical response of lumbar motion segments at high loading rates such as falls or accidents. The vertebral column is the second most common fracture site in high-grade osteoporosis (30-50%) patients and it is the most common fracture during falls (8, 12). This indicates the importance of investigating the mechanical behavior of the vertebral column under vertical impact loading conditions. Impact test machines that have been previously used for biological tissues have certain limitations. In an attempt to overcome some of the earlier limitations of these devices, we designed and fabricated a new drop-weight impact machine to investigate the mechanical properties of lumbar motion segments under impact loading. In this testing device, both force and displacement data are individually recorded with the help of a load cell along with an accelerometer, respectively. Moreover, the device can easily be utilized to measure the mechanical properties of other biological tissues when subjected to the impact loading, which is not possible with the conventional tensile testing devices. Furthermore, the testing results can be used to validate the finite element model of those tissues when subjected to impact loads, e.g., mandibular fracture due to falls or accidents and the advantage of using protective gear can be experimentally examined. Thereafter, the results can be used in validating FEA models to develop the optimized material, thickness, and shape for the protective pad.

First, to verify the measurement accuracy of the sensors and validate this device, the principle of conservation of linear momentum was used to ensure the accuracy of the device's force and acceleration data during impact loadings [Table 1]. Also, a standard uniaxial tensile testing machine was used to calibrate and evaluate the performance of the load cell at different loading rates. All repeatability measurements were performed on a set of polyethylene discs as described above and the results indicated good repeatability and accurate measurements.

The impact test was then conducted on the ovine lumbar segments. Ovine specimens were chosen because they were easily accessible and unlike human specimens, different variables such as age, weight, nutritional diet, genetics and activity levels were more controllable. Likewise, the mechanical properties obtained from the impact testing were compared with those from the quasi-static test.

The test results confirmed that the segment's mechanical properties are sensitive to loading-rate, and with an increase in the latter, the ultimate load to failure of the segment and the specimen stiffness increase, although displacement to failure decreases, which is in agreement with the findings of previous researches [Table 2] (17, 18). When the intervertebral disc was subjected to impact loading, its stiffness increased, but, its shock-absorbing capability reduced significantly. Also, the reduction of shock-absorbing capacity in the intervertebral disc increases the force transmitted to vertebral bodies and surrounding tissues, which is the main cause of vertebral fracture in impact loading, as noted in an earlier study (19). Moreover, in the impact loading, the specimen has higher failure energy compared to the quasi-static loading, which is consistent with the literature (10).

In terms of the damage site, quasi-static loadings at low strain rates have shown that damage occurs at the endplates, whereas, in the impact test, the specimens mostly sustain fractures in the vertebral bodies. In other words, increasing the loading rate affects the site of injury, consistent with clinical observations (8, 18). The cause of vertebral fracture in the impact test is that in loadings of higher rates, the absorbent energy also increases. With an increase in the loading energy, the intra-vertebral disc pressure rises and causes the endplate to swell and eventually leads to a crack in the vertebral body. The bulging of the nucleus material toward the vertebra increases the pressure and eventually leads to a fracture in the vertebra (18).

One of the main limitations of the present study was incrementally increasing the height, which could cause invisible micro- damages to the samples and affect the final failure load, energy, as well as mechanical properties. This effect would be negligible for heights less than 50% of the failure height. Besides, the incremental increase of height does not allow the precise determination of the height needed to cause failure. Also, the experiment was done on animal samples; it would be better if the samples had been taken from human donors in order to model the falling fracture or other traumas on human vertebrae based on numerical solutions and reliable mechanical properties. The small number of samples and the missing information on their conditions before obtaining from the slaughterhouse can be considered as other limitations. The effects of both preload and preconditioning were not directly investigated in the present study and should be examined in future studies. Finally, this study was performed at ambient temperature, thus, investigating the role of body temperature on the impact test results is warranted.

In conclusion, the present study introduced an inexpensive drop-test device, capable of recording both the force and the deformation of the specimens when subjected to high-speed impacts. The device can measure loads up to 20 kN with a duration lower than one millisecond and can be used to measure the mechanical properties of biological tissues under impact loading. To our best knowledge, such a device has not been presented in the literature to date. The use of the setup in testing motion segments showed that vertebrae could be damaged under impact load while damage to the intervertebral disc occurs under quasi-static loads, consistent with other mechanical testing evidence presented in the literature (10, 18). Also, according to the results, an increase in loading rate is associated with an increase in ultimate load to failure, stiffness and failure energy, which is consistent with earlier findings (10, 17, 18).

Disclosures: The authors report no conflict of interests concerning the materials or methods used in this study or the findings specified in this paper.

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