BIOMECHANICAL RESPONSE OF THE LUMBAR SPINE IN DYNAMIC COMPRESSION

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ABSTRACT

The purpose of this study was to investigate the biomechanical properties of the human lumbar spine subjected to dyn compression. A series of six experiments using the lumbar spines from four human cadavers was performed. The fir tests utilized the entire lumbar spine while the remaining four tests used lumbar functional joints to separate the differen stability. A high rate material testing machine was used to produce the dynamic compression at a displacement rate of Custom mounting plates were developed to ensure proper anatomical position of the lumbar spine sections. Both tests the whole lumbar spines resulted in compression fractures at T12 due to combined axial loads of 5009 N and 5911 N bending moments of 237 Nm and 165 Nm respectively. These failures occurred as the spine behaved in first order bu which resulted in concentrated loading and bending of the anterior aspects of the vertebral bodies. All tests with func units resulted in endplate fractures and recorded substantially higher axial loads between 11,203 N and 13,065 N substantially lower bending moments between 47 Nm and 88 Nm. The results indicate that the mechanical stability lumbar spine is critical component in relation to the tolerable compressive loads.

Key Words: Lumbar, spine, dynamic, response, compression, injury, fracture

INTRODUCTION

Injuries to the lumbar spine such as compression fractures can occur in falls as well as automobile aircraft accidents. It is estimated that the cost of spinal fractures in fatal and non-fatal cases is $1 billion per year in the United States [1]. In relatively healthy males and pre-menopausal women, from heights are the primary causal mechanism for spinal compression fractures [2]. Moreover, Ric investigated 101 patients who had been treated for a falls from an average height of seven meters reported that 83% of these patients had injuries to the thoracic and lumbar spine. A similar study Steedman found that the lower limb and thoracolumbar spine injuries were the two most common falls from an average height of 6 meters [3]. In older males and post-menopausal women, or individuals with chronic bone pathologies, lumbar spine injuries can occur from falls from much lower heights su as slipping on ice from a standing height. This increased risk spinal compression fracture predominantly linked to the increase incidence of osteoporosis in women and men over the age of 50 [4,5]. Sugata presented case reports of spinal compression fractures from relatively minor falls, but youngest persons in this study was 61 years of age [6].

Analyzing the literature on the biomechanical response of the lumbar spine is difficult given ma studies present non-biofidelic test methods as they are focused on the treatment and not the cause of injury. For example, Mermelstein presents a very low energy required to cause spinal compression fractures but this was due to the fact that holes were drilled into the bodies to facilitate fracture initiation and thereby substantially weakening the structure [7]. Other studies use only quasi-static loading ra or do not ensure proper load distribution on the vertebral bodies [1]. Therefore, the purpose of this paper is to investigate the biomechanical response of the human spine in dynamic compression usi biofidelic end conditions.

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METHODS

ries was developed that included dynamic compression tests of whole lumbar spines and umbar spine motion segments. For both types of tests configurations a hydraulic Material stem (MTS 810, 22 kN, Eden Prairie, MN) was utilized to apply the dynamic compression nd Figure 2). The MTS actuator deflection was measured using the internal LVDT of the ve axis load cell (Denton, 1968, 22 kN, Rochester Hills, MI) was used to obtain the reaction oment, and a single axis load cell (Denton, 1210AF-5K, 22 kN, Rochester Hills, MI) was in the impactor force. Additionally, accelerometers (Endevco, 7264B, 2000 g, San Juan CA) were placed on both the reaction and impactor load cell plates. In addition, markers d on L1-L4 and high speed video was taken at 1000 fps in order to provide the capability to otion analysis. All cadaver lumbar spine tests were first preconditioned at a rate of 1 Hz and t rate of 0.0001 m/s. All the failure tests were loaded dynamically at 1.0 m/s. For all tests recorded at 50,000 Hz and then filtered to CFC 600.

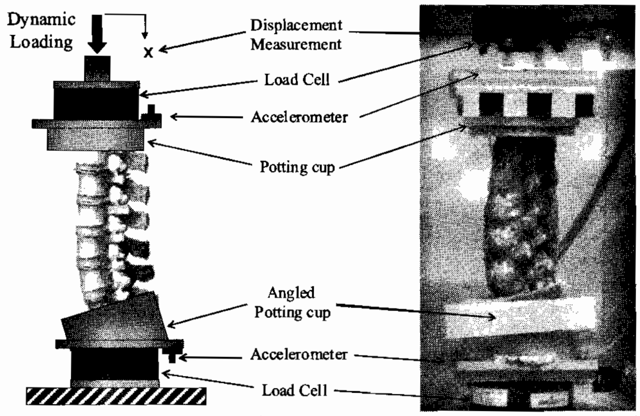

Figure 1: Test configuration for dynamic compression of whole lumbar spines.

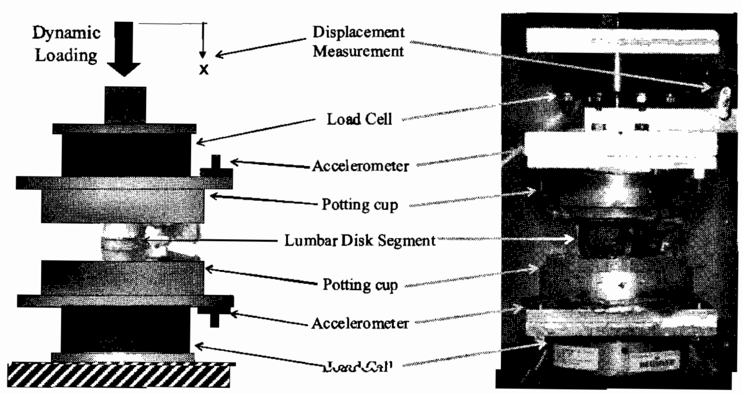

Figure 2: Test configuration for dynamic compression of lumbar spine motion segments.

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A total of six tests were performed using the lumbar spines from four previously frozen unembalmed human cadavers (Table 1). A series of detailed steps were taken in order to ensure the spines were rigidly secured while maintaining the proper testing orientation. For the whole spine tests, all the soft tissue except the ligaments were removed from T12 and L5. Next, a custom potting cup was filled with a bonding compound (Bondo Corporation, Atlanta, GA), and one half of the T12 was placed into the bonding compound. Special care was taken to ensure that the distal end of L5 was at an angle of approximately 18°. The L5 angle of 18° was based on the finding of Makhsous who took radiographs of subjects in upright seating positions, and reported that the average angle of the distal end of L5, relative to the transverse plane, was 17.7 ± 4.8° [8]. Therefore, the whole lumbar spines were potted in an orientation representative of that seen in normal upright seating. The potted vertebral body was then attached to the impactor, and the distal potting cup was filled with the bonding compound. Finally, one half of L5 was lowered into the distal potting cup (Figure 1). The distal potting cup was oriented at a 15° angle in order to provide maximum contact area between L5 and the bonding compound while simulating the angle at which the vertebrae are oriented in the human body. A similar potting method was used by [9].

Table 1: Test matrix and subject data.

Test	Test Specimen	Gender	Age (Years)	Body Weight (Kg)
1	Lumbar Spine: L5-T12	M	66	66.2
2	Lumbar Spine: L5-T12	F	61	44.8
3	Lumbar Segment: L2-L3	M	45	73.9
4	Lumbar Segment: L4-L5			
5	Lumbar Segment: L1-L2	M	45	53.0
6	Lumbar Segment: L3-L4			

A similar technique was used to prepare the lumbar spine segment tests. After the spine was sectioned into the desired units, all the soft tissue except the ligaments was removed. Next, a custom potting cup was filled with the bonding compound, and one half of the proximal vertebral body was placed into the bonding compound. Special care was taken to ensure that the mid-plane of the disc was parallel with the potting cup, and that the disc was centered in the potting cup (Figure 2). This potting orientation has been used by numerous previous authors [10-12]. The potted vertebrae was then attached to the impactor, and the distal potting cup was filled with the bonding compound. Finally, one half of the distal vertebral body was lowered into the distal potting cup. For both whole and segment tests, specimens were lowered into the bonding compound, the bonding compound was allowed to fully before testing. The specimens were kept hydrated during the entire potting process by spraying sa directly on the specimen.

RESULTS

In test 1 with the male whole lumbar spine, the peak axial load at failure was 5009 N with a simultaneous moment of 237 Nm (Table 2). The similar test 2 with the female whole lumbar spine a slightly higher axial load of 5911 N but lower moment of 165 Nm. Both tests 1 and 2 resulted compression fractures at T12 and even after fracture, both lumbar spines were able to support substa loads and moments (Figure 2 and Figure 3). Analysis of the high speed video showed that the lumbar spines exhibited first order bending modes as the compression was applied. This resulted in fractures from the combined axial load and bending moments on the anterior segments of the vertebral bodies.

Table 2: Failure data for the whole lumbar spine tests and the lumbar segment tests.

Test	Test Specimen	Subject Gender	Failure Displacement (mm)	Failure Force (N)	Failure Moment (Nm)
1	Lumbar Spine: L5-T12	Male	9.66	5009	237
2	Lumbar Spine: L5-T12	Female	4.03	5911	165
3	Lumbar Segment: L2-L3	Male	1.94	12777	88
4	Lumbar Segment: L4-L5		2.29	13068	47
5	Lumbar Segment: L1-L2	Male	2.05	11203	83
6	Lumbar Segment: L3-L4		2.04	12597	60

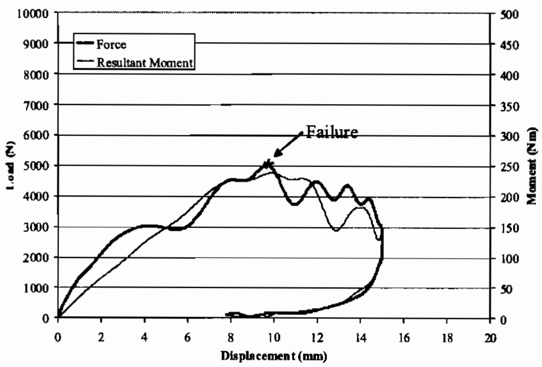

Figure 3: Axial force and bending moment from Test 1.

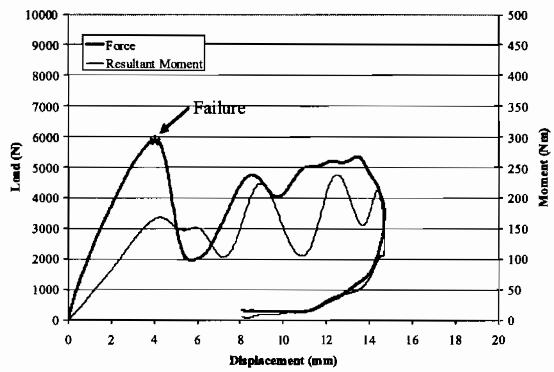

Figure 4: Axial force and bending moment from Test 2.

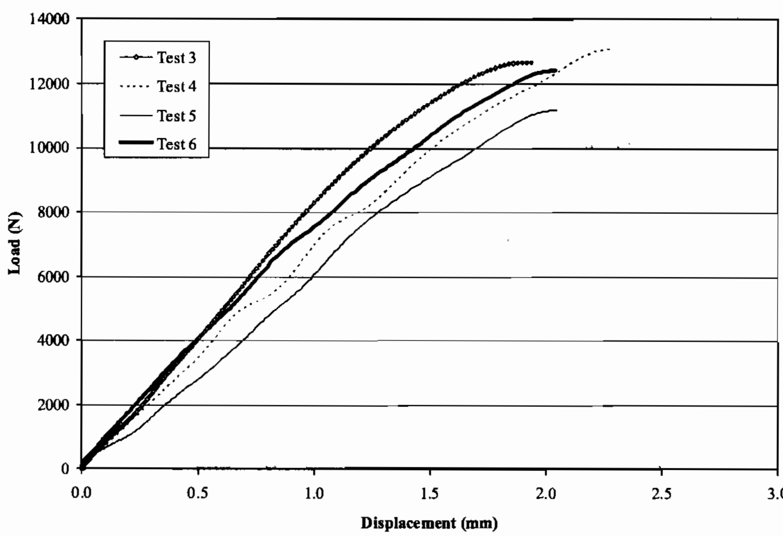

Figure 5: Axial compression load versus displacement for the lumbar segment tests 3, 4, 5, and 6.

All lumbar spine segment tests resulted in superior endplate fractures of the inferior vertebral body. For example, test 3 resulted in a superior endplate fracture of L3. There was no substantial difference between the results for the segment tests, but these results were very different than the whole spine tests. In particular, since only one motion segment was tested, the specimens were very stable and buckling was not possible. This allowed the axial loads to reach double seen in the whole spine testing (Table and Figure 5). Moreover, the moments were reduced in half as well.

DISCUSSION

The whole spine tests illustrated that combined axial load and bending moment can contribute to vertebral compression fractures. Fundamentally, the fracture starts when a local stress or strain exceeds the local tissue tolerance. In these tests, the stress from the axial load and the stress from the bending moment both contributed to the fracture generation. In comparison to the segment tests, the stress from the bending moment was reduced due to the increased stability, and therefore the bone could carry more stress from the axial load prior to failure. It is important to recognize both loading mechanisms, however, most research only presents the axial load as a tolerance even though bending is present.

Previous research by Coltman found that the L1 fracture load for the average population is approximately 7,040 N [13]. Similarly, the Federal Aviation Administration uses a axial load tolerance for the lumbar spine of 6,600 N [14]. Another study involving cadaver specimens found the average burst fracture load for T12 and L1 vertebral bodies to be 6,384 N [15]. Willen also performed tests on human cadaver lumbar spines and found an average failure tolerance of 7,916 N [16]. There are two factors to consider when comparing the axial failure loads of 5009 N and 5911 N for the whole lumbar spine tests to the previous research. First, the two spines in the current study were 66 and 61 years old and likely weaker than the average population. Second, it is difficult to compare the contribution from bending moments in the previous studies as they are often not presented. Given the natural curvature the lumbar spine, it is likely there is always some amount of bending present, but it may be less in the previous studies compared to the current.

CONCLUSIONS

This study investigated the biomechanical properties of the human lumbar spine using whole lumbar spine tests and sectioned functional unit tests. A high rate material testing machine provided displacement rate of 1 m/s to simulate dynamic compression. Both tests with the whole lumbar spine resulted in compression fractures at T12 due to combined axial loads of 5009 N and 5911 N and bending moments of 237 Nm and 165 Nm respectively. These failures occurred as the spine behaved in first order buckling which resulted in concentrated loading and bending of the anterior aspects of the vertebral bodies. All tests with functional units resulted in endplate fractures and recorded substantially higher axial loads between 11,203 N and 13,065 N and substantially lower bending moments between 47 Nm and 88 Nm. These results indicate that the mechanical stability of the lumbar spine is critical component in relation to the tolerable compressive loads. When analyzing spinal compression fracture tolerance data, it is critically important to evaluate the specific loading boundary conditions of a study, the contribution of axial loading and bending moments, and the targeted age population.

The authors wish to th

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