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A Study of Lumbar Injury under Various Loads in Frontal Vehicle Crash

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Abstract:

Background: Although the number of seriously injured cases of frontal impact has been sharply decreased, the spine injury especially the lumber injury is still at high level, thereby resulting in serious consequences.

Objective: This paper is aimed to investigate the lumber injury mechanism in terms of the extension, compression, flexion and rotation loads during the frontal crash using the newly established lumbar model, especially to study the injury mechanism in the lumber disc on a mircoscale.

Method and Material: The detailed new model for the lumbar was used, and the micro index of stress and strain was then investigated to analyze the injury mechanism of the lumber and disc in the crash. Four simple loads were used to represent all the complex loads in the real accident. At last, the correlation of the load types and the micro distribution was discussed to explain the injury reason.

Results: The results show that the disc will have the greatest stress when the loads applied on the sample. The strain in the disc is several times larger than that on the spine, which indicate the disc is the key part when considered the spine injury in the frontal crash. Each load poses its unique strain/stress response on the disc.

Conclusions: The annulus fibrosus of the disc is dangerous under all loads, though the nucleus pulposus of the disc is safe during the impacts. Results in this study can provide a reference to the spine injury biomechanical study and the model can be used in the study of spine cord injury.

Keywords: lumbar, disc, frontal impact, load, strain/stress

1 Introduction

Frontal injury makes up the largest percentage of total traffic accident. Wherein the chest injury accounts for the first of serious injury. With the widespread adoption of the safety technology, the number of injury cases has reduced but the spine injury is not significantly reduced. The spine injury is seldom considered in chest injuries, especially in the lumbar. Its injury percentage is low, however the injury is relatively more severe. Lumbar spine is the only bone between pelvis and chest, thus, if fractures happen in this area, all the functions of the lower body will be heavily limited, and the spine cord injury caused may result in disabling of the lower body, which will cause a life-long burden to society and family.

According to statistics in the US, about 480 cases of full frontal impacts will cause injuries to spine every year. It is noted that nearly all of these were belted and in late model vehicles [1]. Müller finds 126 subjects with cervical spine fractures, and 99 with lumbar fractures among the injury case study of more than 30 thousands traffic accident cases. And the consequence injuries are serious. However, safety equipment will reduce the injury level[2]. There is currently no injury assessment for lumbar spine injury in the vehicle crash standards throughout the world. Compression-related lumbar injuries are occurring in frontal crash impacts and the injury mechanism is poorly understood [3].

From the CIREN database, the lumbar spine injury was mostly happened at the L1 level. Burst fractures in the lumbar occurred predominantly at L1 or L5, moreover, wedge fractures were mostly at L1. Future biomechanical studies are require to focus on reasons for these fractures [3]. The combination of the simulation and test is a useful approach for biomechanics study. Several other researchers have performed studies on the spine injury under frontal crash impact.

Several models have been established to study the kinematic response during impacts, although the detailed model to verify the mechanism and tolerance using the tissue level model is rare. Dewit et al. introduced four loading conditions to study the spine injury in abdomen and predicted peak failure forces was used to study the injury [4]. Wagnac et al. used a newly established bio-realistic finite element mode and found that the strain rate dependent behavior of spinal components played an important role [5]. Travert et al. created a spine model using the medical graphs to predict the spine injury [6]. There are also some studies focused on the disc injury. Among particular implementations, Panzer et al. conducted a simulation based on the validated model using flexion/extension response at the segment level, and the output is disc strains

There are also some studies focused on the disc injury. Among particular implementations, Panzer et al. conducted a simulation based on the validated model using flexion/extension response at the segment level, and the output is disc strains so as to be used to predict injury in automotive impact. But its focus is cervical spine, and lumbar spine is not considered [7]. Flexion-extension and left-right lateral flexion, intradiscal pressure are used by Park to understand the influence of disc on injury outcomes [8]. Furthermore, a three-dimensional finite element model of a lumbar spinal segment L4-L5 with disc was employed to assess the importance of disc to the healthy [9].

The influence of the boundary condition is also documented. El-Rich et al. found that model settings may influence the results. Different loadings will have different injury indexes in the spine. Under flexion, the stress was concentrated at the upper region of L2. Under extension, maximum stress was located in the lower region of L2 [10]. In addition, the mesh types and quality will also have great value to the results [11].

This study is intended to qualitatively analyze distinctive types of stress and strain distribution under different loadings in the disc. It will guide the continuous study of quantitative injury determination and risk prediction. Four simple loadings were used in the study, and the stress and strain distribution of disc was built to discuss its property

2 Method and Material

2.1 Reference whole body results

A whole body model of frontal impact without the restraint of airbag is selected as the reference [12]. This is a sled test to investigate chest injury during frontal crash. The spine curve showed extension, compression, rotation and flexion during the whole impact process (Figure 1). Thus, these four loads were selected as the simple load. During the impact, lumbar especially L1 to L4 was in dangerous (Figure 2). As a result, the detailed models of L2 and L3 as well as the disc between them were established.

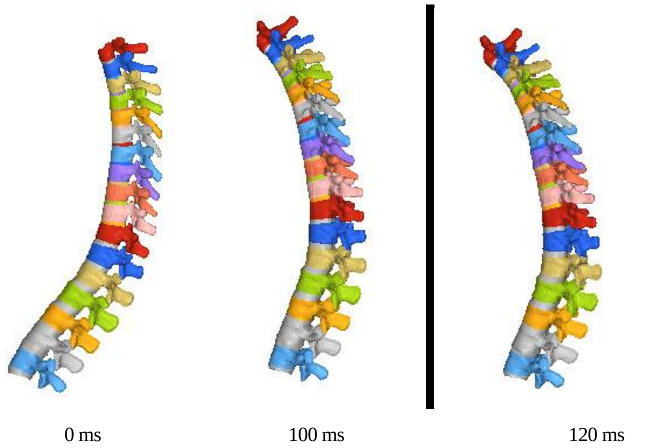


Figure 1. The change of the spine curve during the frontal impact (40km/h)

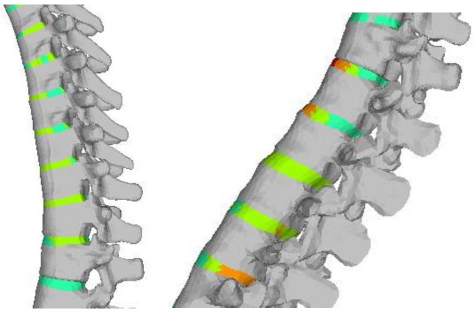


Figure 2. The stress/strain distribution in disc from frontal impact (40km/h)

2.1 Lumbar model

The geometry of the lumbar model was obtained from the CT and MRI of a middle size male. The connection between the bone and disc was ligament. But in the model, all these ligament and spine cord which contained the nerves.had been removed. The bone has been divided into several parts according to their properties. And the cortical bone was simulated by shell elements and the cancellous bone was meshed by solid elements. The disc was also meshed by the solid elements. But the mesh in disc was hexahedron and in the cancellous bone was tetrahedron.

The vertebra was divided into several parts among which the properties were slightly changed. To reduce the environment noise, the muscle and ligament were absent in the model. All the material and thickness parameters were obtained from the references. The model contained 73758 nodes, 335391 elements and 36 parts, which included 2 vertebras and 1 disc (Figure 3).

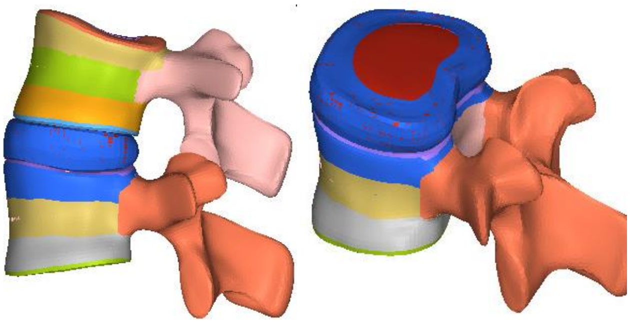


Figure 3. The geometry of the vertebra and disc in the simulation model

2.3 Simulation environment

The bottom of L3 was fixed in all 6 degree-of-freedom. And loads of the impact were applied by the boundary prescribed motion in a vector direction which was normal to the top surface of the L3 on the top surface of L2. The disc and spine were constrained by the tie-break contact. In all simulations, the load velocities were all small in order to have enough time for relaxation of all the spine parts. The simulation environment was similar to the test environment of the other spine tests. There were four simple load being simulated: they were extension, compression, rotation and flexion respectively (Figure 7). Most of the complex load can be a combination of these four. In total of 4 simulations were established for the mechanism study (Table 1), and the simulations were conducted by the LS-dyna code.

Table 1. Simulation matrix

Simulation ID	Load types	Velocity	End time
S1	Extension	1 mm/s	100 ms
S2	Compression	1 mm/s	100 ms
S3	Rotation	0.25 degree/s	40 ms
S4	Flexion	0.25 degree/s	40 ms

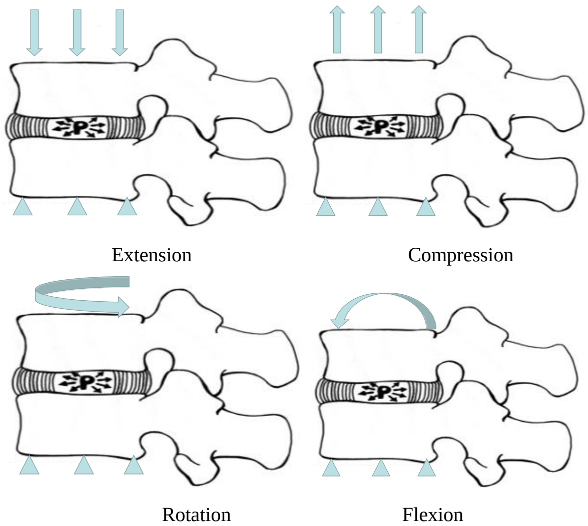


Figure 4. Boundary condition settings in the simulation

3 Results

To better understand the injury mechanism, the stress and strain responses in the disc were captured. Because the velocities were not in the same level, the exact numbers of the stress or strain were not showed in the figure. But the distribution can reflect some of the information about injury reason. Large strain meant the deformation changeed a lot and large stress meant a great change in force. The reason for the injury caused by deformation or force change can be identified using these graphs.

In the extension model (Figure 5), high stress areas were mostly in the disc, especially in the back of the model. This may be caused by the simulation load direction. And the stress distribution of the bone was small. Also, due to the load direction, the high stress area under the compression load was also located in the back of the disc.

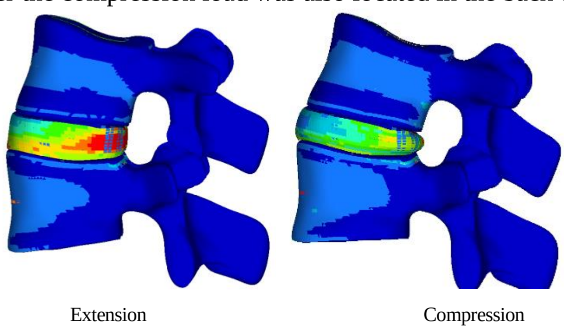


Figure 5. Stress distribution comparison between two loadings

In particular, under compression load, the stresses were mostly in the annulus fibrosus of the disc, and the stresses in the nucleus pulposus were mostly in the outer round. However, the high strain occurred only in the back of the disc, which is different from the stress distribution (Figure 6). This meant that although the force changed much in the annulus fibrosus of the disc, the deformation mostly happened in the back.

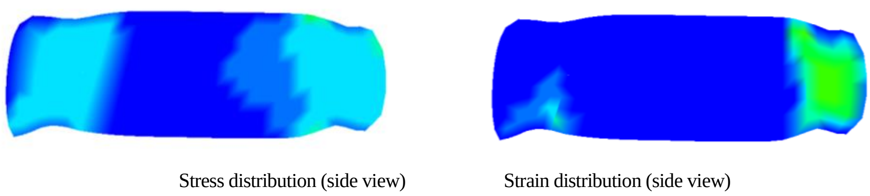
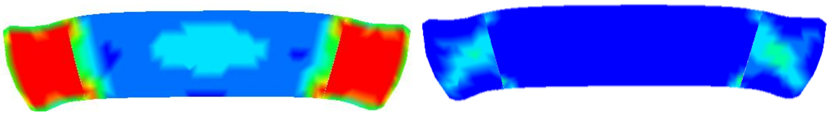


Figure 6. Stress and strain distribution comparison under compression in disc

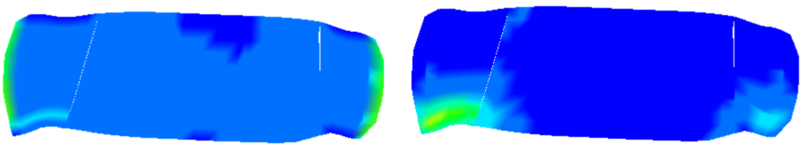
In the case of extension model, the high strains mostly happened in the annulus fibrosus of the disc especially in the outer circle. And stress in the nucleus pulposus of the disc is not very large. Also, strain was also distributed in the annulus fibrosus, and the distribution area was smaller (Figure 7).



Stress distribution (side view) Strain distribution (side view)

Figure 7. Stress and strain distribution comparison under extension in disc

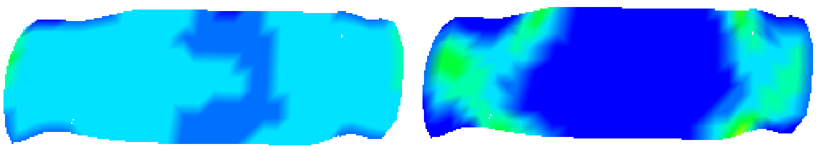
The high stress areas were located in the outer surface of the disc. And the stress in other areas were nearly at the same level, which meant that stress in the nucleus pulposus was also high, although the most dangerous area was the surface judging from the force. Meanwhile, the high strain area was the bottom of disc, especially the frontal area of the disc. The strain in other areas was small (Figure 8).



Stress distribution (side view) strain distribution (side view)

Figure 8. Stress and strain distribution comparison under rotation condition in disc

In the flexion condition, it was difficult to identify the high stress area. This is because all parts of disc were at the same stress level though the stress in the center was a little lower. However, in the strain distribution, the high strain only happened in the outer circle of the annulus fibrosus. As a comparison, the strain in the nucleus pulposus of disc was small (Figure 9).



Stress distribution (side view) strain distribution (side view)

Figure 8. Stress and strain distribution comparison under flexion condition in disc

All load types have the unique stress or strain response in terms of distribution in the disc. These distribution patterns can reflect the most venerable area during the loading or the injury reasons.

4 Discussion

4.1 Influence of ligament

In this study, there is no ligament or muscle in the spine model in order to reduce or avoid the environment noise and make the study simple. But in the real accident, the ligament will play a key part to the injury outcome especially in the extension, flexion and rotation processes. The existence of ligaments will reduce the stress and strain in the loading condition. Therefore, values obtained in this study are not the real ones, but the distribution can reflect the real response trend to loads.

4.2 Influence of age

The material parameters of bone and soft tissue will change with the increase of age due to the loss of calcium. However, one definition of the bone and tissue was used in this study, which means the model is established for a certain person. In this case, the responses under the load are unique but not universal. However, the results of distribution in the study can show a trend of the injury mechanism especially in the disc.

4.3 Complex load

Loads in the spine are complex, but most of the time they can be divided into two types-extension and compression. There are also rotation and flexion or a combination thereof. In this case, the load condition in frontal crash is very complex. However, every loading can be of several loading types, though the exact values are different. In the mechanics study, the simple load is a key factors to explain the injury.

4.4 Restraint systems

The seatbelt can restrain the body, but due to the heavy load, the spine will be injured by the load. Thus, the unsuitable use of the restraint system will cause injury to the spine. Actually, the influence of impact loadings are highly dependent on the restraint systems. The injury outcomes in the spine may be greatly influenced by the protection efficiency. For example, the wearing of the seatbelt and the height of the occupant which may affect the efficiency of the restraint system. As a consequence, they may affect the injury outcome based on the above discussion. Other boundary conditions will also have an influence them, but a study shows that 40 km/h is the mean impact velocity for the most common spine injury.

5 Conclusion

The injury mechanisms of lumbar and disc are analyzed based on the bio-fidelity model under various impact load. The strain/stress are used to study the relationship between injury micro indexes and load types.

There are three novel aspects in this study. First, the complex load is divided into four simple loads which can represent the load characters and be more realistic. Second, in addition of the bone injury, the injury outcome of disc is also investigated. Both mechanisms can vividly and fully explain the injury mechanism of spine. Third, the new model is divided into several parts based on the material or simulation theory, which may be more detailed than other researches about the spine injury.

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