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A Study of Lumbar Disc Injury under Typical Frontal Impact Load

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Keywords：lumbar injury, spine disc, frontal impact, load pattern, strain/stress distribution.

ABSTRACT

Although the number of seriously injured cases of frontal impact has been sharply decreased, the spine injury especially the lumber injury is still at a high level, thereby resulting in serious consequences. 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 microscale. A new detailed 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 disc in the regulation frontal crash. The complex load can be divided into several representable load patterns. Four representative loads were used to reflect the loads in real accident. At last, the correlation of load types and the micro distribution was discussed to describe the injury mechanism. 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 indicates the disc is the crucial part when considering the spine injury in the frontal crash. Each load poses its unique strain/stress response on the disc. 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 used in the study of spine cord injury.

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INTRODUCTION

Frontal crash injury accounts for the largest percentage of total traffic accident injuries. Wherein the chest injury accounts for the first of serious injury (Newgard, 2008). With the widespread adoption of the safety technology, the number of injury cases has been significantly reduced, but the number of spine injury is not (Bambach *et al.* 2013). However, the spine injury is seldom considered in chest injuries, especially in the lumbar. Because its injury percentage is low though the injury is relatively more severe. Lumbar spine is the only bone between pelvis and chest, thus, if fractures or injuries happened in this area, all the functions of the lower body will be heavily limited. The spine injury may result in disabling of the lower body, which will provoke a life-long burden to society and family (Wang *et al.* 2009).

According to statistics in the US, about 480 cases of full-frontal impacts will have spine injuries each year. It is also noted that nearly all of these were belted (Kaufman *et al.* 2013). Müller finds 126 subjects with cervical spine fractures, and 99 with lumbar fractures among the injury study of over 30 thousand traffic accident cases. Consequence injuries are serious though safety equipment will reduce the injury level (Müller *et al.* 2014). There is currently no injury assessment for lumbar injury in the vehicle crash standards throughout the world. Meanwhile, compression-related lumbar injuries are occurring in frontal crash impacts and the injury mechanism is insufficiently understood (Pintar *et al.* 2012).

From the CIREN database, the lumbar spine injury was mostly happened at the L1 level. Fractures in the lumbar occurred predominantly at L1 or L5. Future biomechanical studies are required to focus on reasons for these fractures (Wang *et al.* 2009). In one of the study cases of the traffic frontal impact, the L3 level is the in a very huge risk of fracture due to the compression and bending (Pesenti *et al.* 2016). 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 (Conroy *et al.* 2016; Fice *et al.* 2012; Abbas *et al.* 2011). 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 not sufficient (Panzer *et al.* 2011). Dewit introduced four loading conditions to study the spine injury in the abdomen area and predicted peak failure forces of the spine injury (DeWit *et al.* 2012). Wagnac used a newly established bio-realistic finite element model and found that the strain rate dependent behavior of spinal components played an important role in the injury (Wagnac *et al.* 2012). Travert created a spine model using the medical graphs to predict the spine injury (Travert *et al.* 2012). However, the deeply study with detailed model is still not enough. Among all the restraint loadings, seatbelt load was identified as the primary load in the frontal impact which can cause a high risk of fracture in the L2 and L3 (Čertík *et al.* 2016). One investigation showed that the seatbelt load may heavily associate with the spine injury in the area of abdomen (L1 to L4) (Parenteau *et al.* 2018). Thus, in the study of lumbar injury from frontal crash, the seatbelt load should be carefully considered.

The disc injury also attracts the focus in the recent years. Among particular implementations, Panzer conducted a simulation based on the validated model using flexion/extension response at the segment level. The output is disc strains which can be used to predict injury in automotive impact. But its focus is cervical spine, and lumbar spine is not considered (Panzer *et al.* 2011). Flexion-extension and left-right lateral flexion, intradiscal pressure is used by Park to understand the influence of disc on injury outcomes (Park *et al.* 2013). Furthermore, a three-dimensional finite element model of a lumbar spinal segment L4-L5 with disc was employed to assess the importance of the disc to the health (Ye *et al.* 2018). Ye did a factor analysis study about the spine injury tolerance in the lumbar using the normal restraint systems, of which the area from L2 to L4 would have the likelihood in fracture especially in the load of bending (Ye *et al.* 2018). Moreover, in different restraint systems, the load environment in spine would be different, and the mostly happened fracture would be compression and burst fractures (Rao *et al.* 2016).

The influence of the boundary condition is also documented. Researchers found that model settings may influence the results (Wagnac *et al.* 2009). Different loadings will have distinct 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 (El-Rich *et al.* 2009). In addition, the mesh types and quality will also have great value to the results (Lalonde *et al.* 2013).

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 typical loadings were used in the study to discuss the property.

METHOD AND MATERIAL

Reference whole-body test results

A whole-body model of frontal impact without the restraint of airbag is selected as the reference model (Shaw *et al.* 2009a). This is a sled test aimed to investigate chest injury during frontal crash at 40 km/h. this impact velocity is selected according to a study the results of which is that 40 km/h is the mean impact velocity for the most common spine injury. Due to the existing of the seatbelt, the rotation and flexion are obvious. The spine curve showed extension, compression, rotation and flexion during the whole impact process in some certain locations (Figure 1). Thus, these four loads were selected as the simple load. And all the boundary condition of the local area is the same as the sled tests. During the impact, lumbar especially L1 to L4 was in dangerous judging from the figure at 80 ms after the initial crash (Figure 2). As a result, the detailed models of L2 and L3 as well as the disc between them were established, and this study unit is selected as the loading sample.

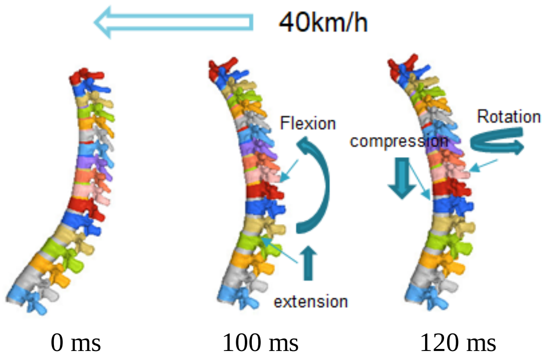

Fig. 1. The local loads of the spine curve during the frontal impact

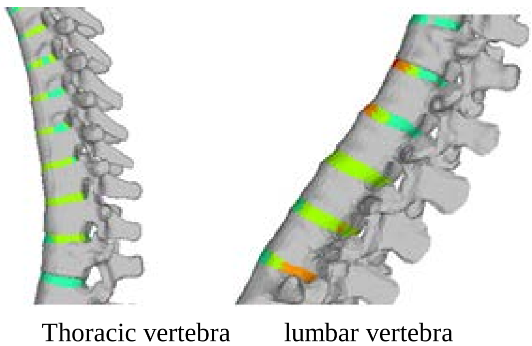

Fig. 2. The stress/strain distribution in disc from frontal impact

The reference test was conducted via the simplified sled, in which the common seatbelt load was applied and the general constrain of the occupant were obtained from a middle size vehicle in US (Ford Taurus). There is no airbag or side curtains. The knee bolster was placed under the knee of the occupant. A deceleration pulse was applied on the sled to simulate the kinematics of the car in during the crash under 40 km/h. There were eight similar tests with the similar size PMHS (similar to the 50th Hybrid III dummy) (Shaw *et al.* 2009a). The reference test is the GS1 test condition which is established based on the middle size vehicle driving condition (Shaw *et al.* 2009b). The localized load of the lumbar intervertebral disc is captured from the reconstruction of these tests via numerical simulation.

Lumbar model

The geometry of the lumbar model was obtained from the CT and MRI of a middle size male. In the model, all ligaments and spine cord which contained the nerves had been removed. And the cortical bone was simulated by shell elements and the cancellous bone was simulated by solid elements. The disc was also simulated by the solid elements though the mesh type in disc was hexahedron and in the cancellous bone was tetrahedron.

The study of spine unit is conducted by the unit of L2 to L3, which included 2 vertebras and 1 disc. Usually, the most venerable part of the spine is cervical vertebra, and followed by the lumbar. While in this study, the injury in the lumbar was investigated through the combination loads from impact energy of the car and the load from the restraint systems. Meanwhile, it is found that the L3 level is the mostly dangerous parts of fracture (Čertík *et al.* 2016), (Ye *et al.* 2018). Thus, the unite in L2 and L3 is applied in this study. And this spine unit is also regraded as the most dangerous element unit of an occupant during the frontal crash. Thus, this study can reflect the lumbar injury during the frontal crash. To study this unit in detail, the model method of this part is meshed with others pervious results (Lalonde *et al.* 2013). In detail, 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 materials and thickness parameters were obtained from the references (Wagnac *et al.* 2012), (Wagnac *et al.* 2011). The model contained 73758 nodes, 335391 elements and 36 parts (Figure 3). The vertebras and disc are divided into several parts according to the different properties of the material, which has been validated to be better in simulating the biomechanical responses in the injury study (Fradet *et al.* 2014).

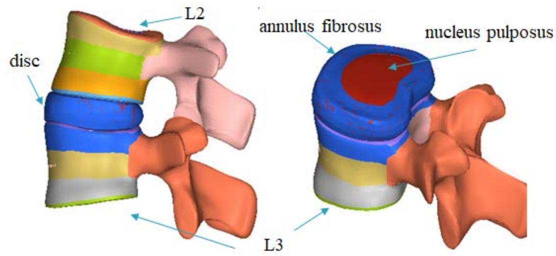

Fig. 3. The model of the vertebra (L2-L3) and disc

Simulation environment

The bottom of L3 was fixed in all 6 degree-of-freedoms. The load of the impact was applied by the boundary prescribed motion in a vector direction which was at the top surface of L2 and normal to the top surface of the L3. The disc and spine were constrained by the tie-break contact. In all simulations, the load velocities were 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 loads being simulated: extension, compression, rotation and flexion respectively (Figure 4).

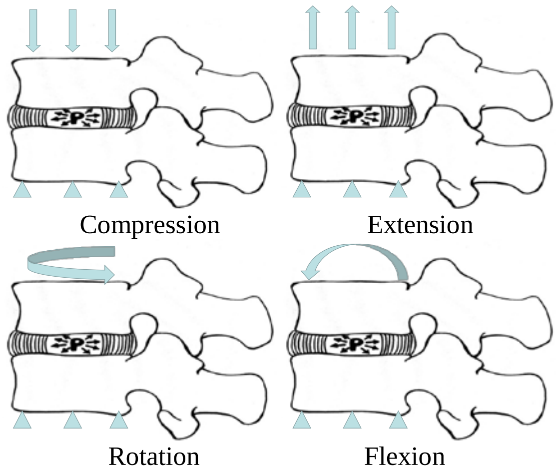

Fig. 4. Boundary condition and loads in the simulation

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. All the load conditions are simplified from the occupant test and has been verified can reflect the occupant response during the impact. The kinematics and injury level had been analyzed. Judging from the kinematics and load path from the occupants, some venerable parts were obtained, in which one of the serious risk parts in the lumbar was L2 and L3.

Table 1. Simulation matrix

Simulation ID	Load types	Velocity	End time
S1	Extension	1 mm/s	120 ms
S2	Compression	1 mm/s	120 ms
S3	Rotation	0.25 degree/s	50 ms
S4	Flexion	0.25 degree/s	50 ms

RESULTS

Because the load of this spine unit is applied refer to the occupant loading condition in the frontal crash, the results of the unit can reflect the injury risk and injury patterns during the impact.

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 and the exact numbers of the stress or strain only can show the peak under different load. The stress and strain distribution can reflect the information about injury reason. Large strain rate meant the deformation changed a lot and great stress meant a great change in inner force. The reason for the injury caused by deformation or force change can be identified using these graphs. The unique biomechanical response can represent the injury patterns caused by different loads. Meanwhile, the relationship between the load and response patterns may explain the injury mechanism caused by the complex load.

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 located in the back of the disc. In particular, under extension 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).

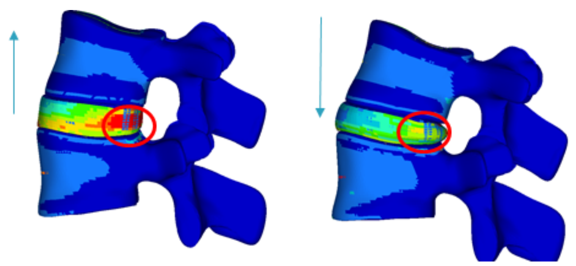

Fig. 5. Comparison of stress distribution between two loadings

This meant that although the force changed much in the annulus fibrosus of the disc, the deformation mostly happened in the back. In the case of compression 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). 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). 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).

The peak stress value was captured in the rotation condition, which meant this load may highly affect the safety of the lumbar intervertebral disc especially in the area of outer annulus fibrosus. This might because the annulus fibrosus was the main contact parts between two vertebras and the tissue in this part was in low liquidity. As a comparison, the smallest one was in compression, and the peak value happened in the center of annulus fibrosus. The reason may that this part was the main component of connecting. Most of the results of the stress distribution were symmetrical judging from the middle section view. Meanwhile, judging from the cross-sectional view, the strain distribution was asymmetrical. The maximum of the peak strain happened in the rotation condition too. And most of the high strain area were located in the annulus fibrosus especially in the back area. The load velocities were not in the same level, which meant a combination of several typical loads may be more meaningful in the study.

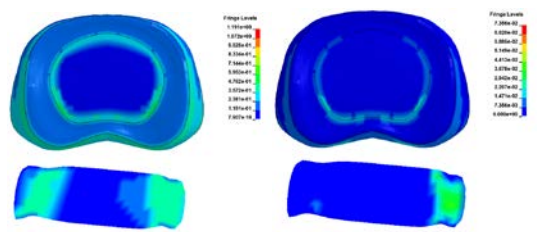

Fig. 6. Comparison of stress and strain distribution under extension in disc (80 ms)

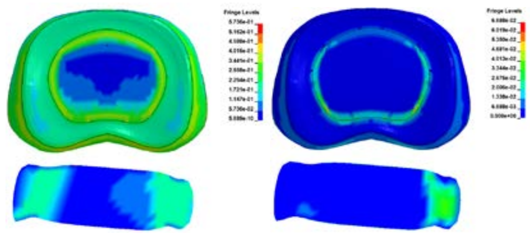

Fig. 7. Comparison of stress and strain distribution under compression in disc (80 ms)

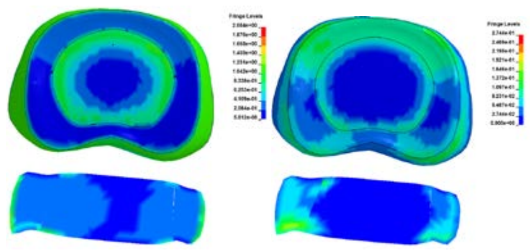

Fig. 8. Comparison of stress and strain distribution under rotation condition in disc (40 ms)

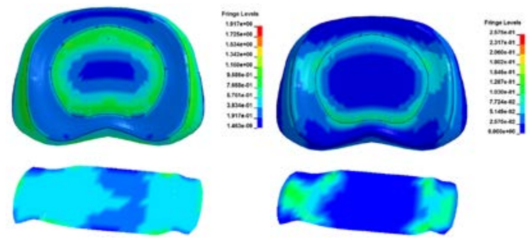

Fig. 9. Comparison of stress and strain distribution under flexion condition in disc (40 ms)

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. Furthermore, the combination of these results can explain the injury response in the lumbar disc with more complex load conditions.

DISCUSSION

Influence of ligament

In the present 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 may play a key part to the injury outcome especially in the extension, flexion and rotation processes (Radcliff *et al.* 2012). 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. So, further studies with ligaments or muscles may be conducted to discuss the influence of these soft tissues on spine injury outcomes. The stiffness of the spine will also be influenced by the function of these ligaments or muscles, which may result in the injury outcome difference (Ji *et al.* 2017).

Influence of age

The material parameters of bone and soft tissue will change with the increase of age due to the loss of calcium (Zhang *et al.* 2012). However, one definition of the bone and tissue was used in this study, which means the model is established for a certain person at a unique age. Lumbar disc herniation and deterioration that often happened in the elderly may greatly affect the shape of the disc. These changes of disc may lead to results change to spine loadings. 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.

Complex load

According to the whole-body test, loads on the spine are complex. In this case, the spine load condition in frontal crash is very difficult to distinguish or describe (de Schepper *et al.* 2010). But most of the time, they can be divided into two types-extension and compression. There is also rotation and flexion or a combination thereof. However, every loading can be of several loading types, though the exact values are different. In the mechanics study, the simple load is a critical factor to explain the injury. Especially that the precrash positioning of the occupant may increase the risk of lumbar injury in frontal crash (Derek *et al.* 2016). Thus, the injury responses to the typical load from frontal crash is representable of the complex load environment. The response of the complex load on the spine can be reflected by the combination of the stress and strain distribution obtained from the simple load simulation.

Since the spine is not straight and has the physiology curve (Howes *et al.* 2015). Thus, the load applied on the vertebra is not really along the curve. As a result, the compression load is a micro index on the spine unit in this study. Nevertheless, for the disc, some parts may be extended by the compression load during the load period. Also, the disc is not a flat tissue, which means the contact between vertebra and disc may not happen at the same time.

Restraint systems

The seatbelt can restrain the occupant body. But due to the heavy load, the spine will be injured by the restraint load at the same time (Abbas *et al.* 2011). Thus, unsuitable use of the restraint system will cause injury to the spine. Actually, the influence of impact loading is highly dependent on the restraint systems. The injury outcomes in the spine may be strongly 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 will also influence the injury outcomes. Other boundary conditions will also have an influence on them (Patalak *et al.* 2018). Consequently, they may affect the injury outcome based on the above discussion.

The existing of seatbelt may increase the risk of rotation/flection and decrease the risk of compression and extension. And airbags will also play a part during the impact process to reduce the considerable deformation of the spine. Knee restraint will also lead to upper body rotation in the spine, which may cause excessive spinal flexion (Ji *et al.* 2017). At the same time, the seating posture of the occupant affected by the seat may affect the spine curve, which is important for the dynamic response of the spine.

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.

The lumbar is serious injured due to the exclusive movements in the forward direction and bending rotation during the frontal impact. And the restraint system may heavily influence the loading environment of the localized lumbar unit. In this study, the unit of L2 and L3 is investigated through the four typical loading on the unite. Among the four reactions, the outer circle of the disc is sensitive to the change of load types and the inner part is not so obviously influenced. Meanwhile, the level of the injuries mostly happened in the surface of the contact area.

There are three novel aspects in this study. First, complex loads are divided into four typical loads which can represent the load characters. Second, in addition to the bone injury, the injury outcome of the disc is also investigated. Both mechanisms can fully explain the injury mechanism of spine. Third, the lumbar unite model is divided into several parts based on the material or simulation theory, which may be more detailed than the former methods.

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典型正面衝擊載荷下腰椎間盤損傷的研究

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摘 要

雖然在正面碰撞事故中人員受到嚴重損傷的情況急劇減少，但是因為脊柱損傷尤其是腰部脊椎損傷導致嚴重損傷的事故統計依然很多。本文旨在利用新建立的精細化分塊腰椎生物力學模型研究當乘員受到正面碰撞時在脊椎單元上受到拉伸，壓縮，扭矩，彎矩等代表性載荷造成的腰部脊椎特別是腰間盤所受的損傷分佈特徵，特別是研究微觀腰椎間盤損傷特徵機制。結果表明，當載荷施加在脊椎單元樣本中時椎間盤將會有最大的應力，椎間盤中的應變比椎體上的應變大幾倍。本研究結果可為脊柱損傷的生物力學研究提供參考，該模型亦可用於脊髓損傷的生物力學數值研究。