Proceeding of the 13th International Forum of Automotive Traffic Safety, 2016, pp 520-533
No.ATS.2016. 509

A Study on Injury Mechanism of Cervical Spinal Cord in Frontal Impact

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Abstract: The incidence of cervical spinal cord injury in vehicle collisions is common. However the specific mechanism of spinal cord injury is not clear. The aim of this study was to discuss the mechanism of the cervical spinal cord injury during vehicle collision via Finite Element Analysis (FEA). A complete cervical spinal cord model with detailed anatomical structures of gray matter, white matter, pia mater, dura mater and cerebrospinal fluid was developed and validated. This model was then assembled with a well-validated head-neck FE model. In order to simulate the biomechanical response of spinal cord in frontal impact, the assembled model was merged with Hybrid III FE model by replacing the head and neck parts. Different intensities of frontal impact were simulated. The results showed that ventral white matter's lesions were more serious than the dorsal white matter. The greatest stress of cervical spinal cord was found in the level of atlas that may be caused by the excessive relative motion in atlantoaxial joint. Meanwhile, the higher stress in vertebra was found in the level of fifth and sixth cervical vertebras that may result from the narrow spinal canal. Damage of intervertebral disc in high intensity impact will lead to the excessive compression in spinal cord.

Keywords: biomechanics; finite element analysis; spinal cord injury

1 Introduction

With the amount of automobile ownership climbing steadily, the incidence of traffic accidents is greatly increased which brings huge burden to the social economy as well as makes lots of trouble for personal life. 1.2 million people are killed in road traffic accident each year as many as 50 million are injured[1]. There are variety of crash types including frontal impact, side impact, rear impact and rolling impact. In traffic accidents, frontal impact roughly occupies more than 50 percent has a larger incidence than any other impact type[2] and some investigation figures are explained in Table1. Among the frontal impact, the cervical injury is most common injury type and 83 percent of traffic victims had experienced cervical injury[3-6].

Once the frontal car collision occurs, the brain and neck would suffer sudden force and acceleration that makes neck produce deformation in short time and leads to spinal cord injury during the process of crash. More recently, literature that offers investigation findings about the spinal cord injury has emerged. About 10.4 to 83 million people will suffer spinal cord injury every one million people and 55 to 75 percent of those people had hurt cervical spinal cord. Cervical spinal cord injury will acquire a long and complicated treatment process as well as huge medical expenses, quite a lot of patients will experience obvious sequelae following all of his or her life. There is no obvious cognition for the mechanism of spinal cord injury caused by traffic accident so that it is no effective method to for cast and prevent this injury. Therefore, it is indispensable for this paper to develop a effective model to explain the injury mechanism of spinal cord which will play an important role in clinical treatment.

Currently, the study of cervical injury mechanism during the frontal crash has been a controversial subject within the field of biomechanics, there are also quantities of debates for spinal cord injury. Firstly, several studies have designed a series of autopsy experiments with variety of crash conditions[7] and played an irreplaceable role in the study of human injury biomechanics. However, spinal cord from autopsy has weak mechanical property comparing with the spinal cord in vivo, therefore, there has a great rising space among the research. Secondly, using the animal model to simulate the injury process will provide valuable research data for subsequent investigations[8]. However, the anatomical structure of animal exists great difference compared with human body. Thirdly, the results of volunteers experiment that is only used in low crash speed from vehicle collision is the most real reaction of body. This kind of study does not apply to the high crash speed because of the limitation of volunteer's safety and ethical problem[9]. Finite element analysis(FEA) has gained unparalleled advantage in the study of vehicle crash as a new research method. Finite Element

Model(FEM) will reveal the injury process of spinal cord and show the dynamic stress change process combining with clinical information, which might explain the injury mechanism and provide guidance for clinical diagnosis and treat

ment. The relevant FEM that include the spinal cord have been developed among the quantitative studies of injury mechanisms of spinal cord[10-12]. There are some articles explaining the spinal cord injury mechanism by developing a computational three-dimensional (3D) FEM of spinal cord[13]. A valid human FEM that contains mainly structure including skeletal, muscle, ligament[14]. The model has high fidelity of creatures, which will help studying the dynamic response when quantity of load conditions are used in different displacement, velocity and acceleration among car-crash research. However, it is not include spinal cord model. In this paper, a complete cervical model with skeleton, muscle, ligament and spinal cord was developed, and series of experiments were developed to valid the model. Finally, the model was assembled with 50thhybrid III dummy model, and the impact tests of different intensities were carried out. The objectives of this research is to explore the injury mechanism of cervical spinal cord using the hybrid model described above in low, medium and high intensity impact respectively.

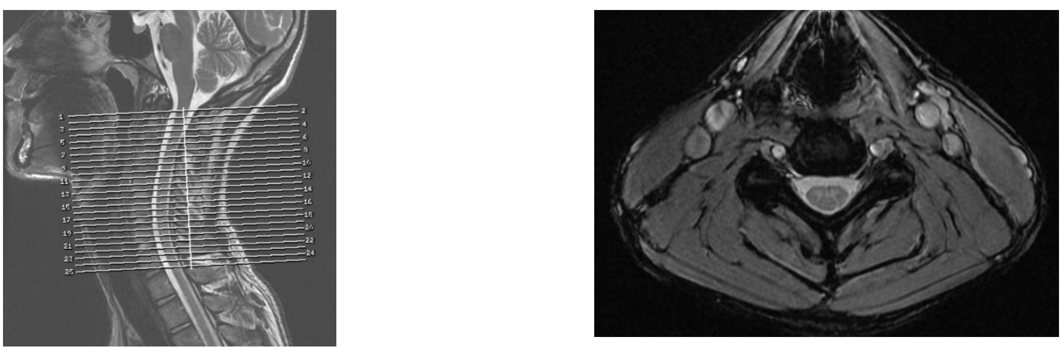
Table 1. The proportion of different accident type in some of the country(%)

Country	frontal impact	side impact	rear impact	rolling impact
Japan	49	27	9	15
America	54	29	3	14
French	57	31	2	10
Germany	63	30	4	3
Italy	57	25	12	6
England	64	22	3	7
Austrilia	62.2	32.3	5.5	-

2 Methods

2.1 Cervical Spinal Cord FEM Generation and Validation

This study selected one healthy 50th adult male volunteer whose age is 19 years old with 169 cm height and 63 kg weight. The volunteer is proved to be healthy without any cervical disease through X ray, the CT of cervical vertebra and the spinal cord MRI. Volunteers took supine condition on board of nuclear magnetic resonance (NMR) machine that scans the volunteer’s body from first cervical vertebra to seventh cervical vertebra continuously until profiles of the gray and white matter is clearly visible as is shown in Figure1. The data whose format is Dicom from the MRI image will be imported into Mimics software to obtain a smooth three-dimensional geometrical model of spinal cord. A single cross section of spinal cord was stretched around 100 mm in the vertical direction to gain a validation test model(the simplified model) while three-dimensional geometrical model of spinal cord was built by several cross section applied to study the injury mechanism. The simplified model was constitute of gray matter and white matter because the tensile test only consists of gray matter and white matter is an animal test in vitro[15]. The simplified model can keep consistent with the test specimen in existing literature and ensure the effectiveness of validation test. Figure 2 shows us the simplified model and three-dimensional geometrical model of spinal cord that contains gray matter, white matter, pia mater, dura mater and cerebrospinal fluid (CFD). Cross-sectional structure of the spinal cord as shown in Figure3.The gray matter area is butterfly-shaped and located in the center of the spinal cord, the white matter area is located in the periphery of the gray matter as well as pia mater wraps white matter.



(a) **(b)**

Figure 1. (a) Sagittal plane of spine and cervical spinal cord in MRI (b) Cross section of spine and cervical spinal cord in MRI

(a) **(b)**

Figure 2. (a) The simplified model of spinal cord (b) Three-dimensional geometrical model of spinal cord

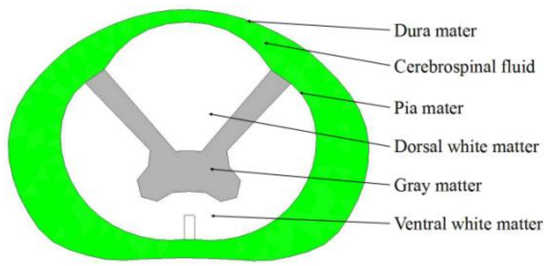


Figure 3. Cross-sectional structure of the spinal cord model

The models were divided by tetrahedron element(the grid size is from 0.5 to 1mm) while the pia mater and dura mater was divided by triangle element. Some research findings on the material performance demonstrate that gray matter, white matter, pia mater and dura mater are piecewise-linear and elastic-plastic while the cerebrospinal fluid is viscoelastic. The stress-strain curve as is shown in Figure 4 explains the material performance accurately and all the material performance are summarized in Table 2.

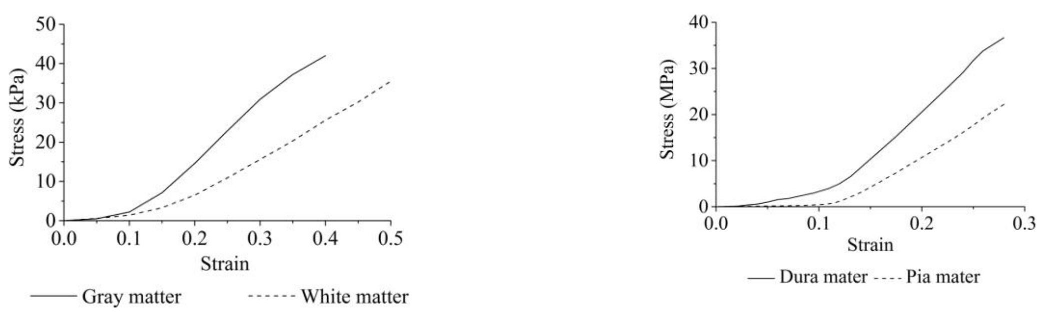
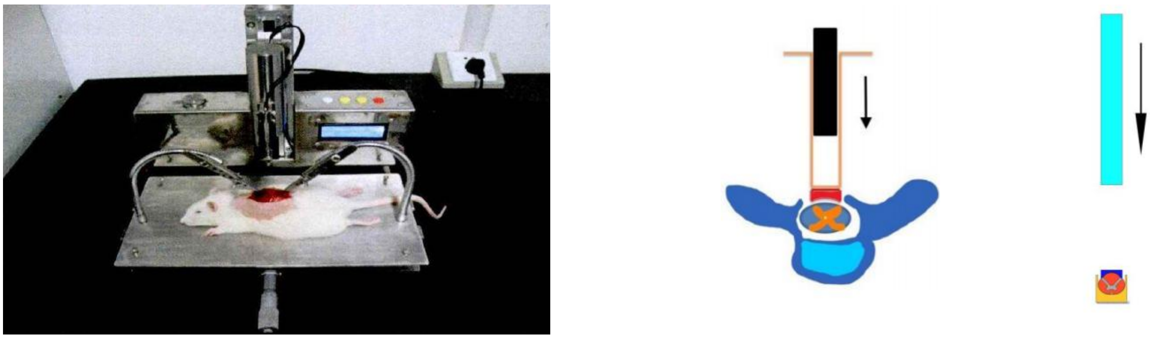


Figure 4. Material stress-strain curves

Table 2. Material mechanics performance of the anatomy structure in model[16-22]

Structure tissues	Density(Kg/m^3)	Mechanics performance
white matter,	1050	Figure 4
gray matter	1050	Figure 4
pia mater	1140	Figure 4
dura mater	1140	Figure 4
cerebrospinal fluid	1040	BULK=2190MPa
		G0=1.0kPa
		G∞=0.9kPa
		B=80s^{-1}

The finite model was verified to ensure the model can reflect real mechanical performance of spinal cord. Two validation tests, compression test and tensile test based on the animal mechanical tests of the spinal cord in vivo. The animal compression test was developed by Jianzhong Hu et al.[23] as well as the animal tensile test in vitro was developed by Maiman et al.[15], Xin-Feng L et al.[24]has developed a FEA validation test according to Maiman's study. Jianzhong Hu et al. applied electronic-control gravity hammer device of Allen to conduct a hammer test of rat's spinal cord. In this experiment, the hammer weighing 8g drops to the pad on the dura matter from 4cm height freely, after that the dropping test, they gained the blood vessel image. This paper built the FEM of hammer test according to the stress equivalence principle that the hit force in unit area should be equal when the drop height is consistent, as shown in Figure 5. In Maiman's study, traction including 5kN,10kN and 15kN is applied to spinal cord respectively. This paper made 3 groups quasi-static tensile tests using the FEM of spinal cord, as shown in Figure 6.



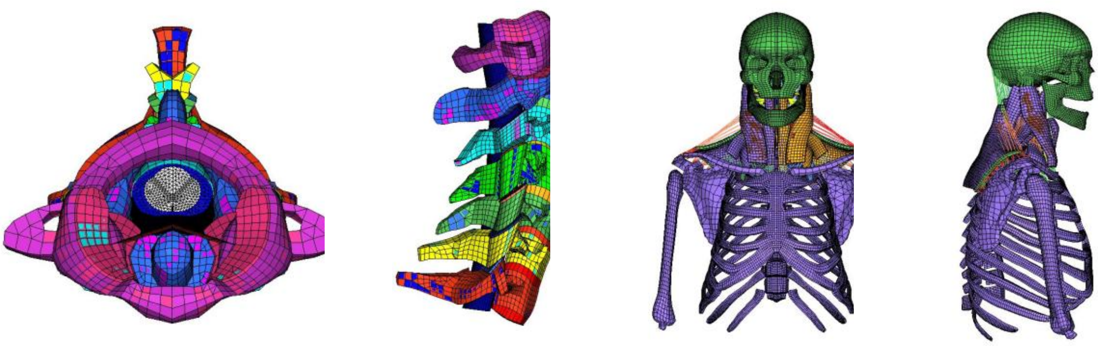
(a) (b) (c)

Figure 5. (a) Hammer impact experiment of rat's spinal cord; (b) Schematic diagram of hammer impact experiment of rat's spinal cord; (c)The simulation of hammer impact model

Figure 6. Tensile test FEM model of simplified spinal cord

2.2 Hybrid Dummy FEM Generation and Validation

The FEM of spinal cord was assembled with head-neck complex model (Figure 7(b)) which was built by Fan Li et al.[25, 26]. Fan Li et al, as shown in Figure 7(a). established the fundamental model by deleting the brain and neck in Hybrid III model (Figure 7(d)).The hybrid model (Figure 7(d))was verified by C.L. Ewing's sled experiment[27], the validation test result explained that the data is consistent with the experimental data of volunteer.



(a) (b)

(c) **(d)**

Figure 7. (a)Sipne cord assembled with the cervical vertebra; (b) Fundamental FEM of head-neck complex that contains muscle geometry feature and active response of muscle; (c) Hybrid III dummy model; (d) Hybrid FEA model

In the 1970s, in order to study the kinematic response of human head-neck complex in impact environment, Ewing et al.[27] carried out several volunteer sled tests. As a result of the Ewing's volunteer experimentation, a large number of kinetic parameters were obtained for relevant studies, which laid the foundation for the further study, so the numerical model of the head-neck complex is verified by the results for many times. During the test, the volunteer was asked to sit on the seat of the sled and use the webbing to restrain them. The hydraulic device at the rear of the vehicle impacts the sled, making the sled produce the acceleration to hit the frontal rigid barrier so as to simulate the front collision. The motion parameters of the head and the 1st thoracic vertebra in three directions were captured by multiple high-speed cameras and acceleration sensors. As shown in Figure 8, the peak acceleration of the sled is set to 15G and the speed change is greater than 17m/s in the test. The acceleration curve generated by the hydraulic impactor in the test is the input curve of the motion. This paper will verify whether the model is valid by comparing the relative rotation angle curve of head and the synthesis acceleration of head centroid by Ewing's test. The simulation time for the pre-crash simulation test is defined as 200 ms because that the important kinetic data returned to a low level at 200 ms according to Ewing's survey[28].

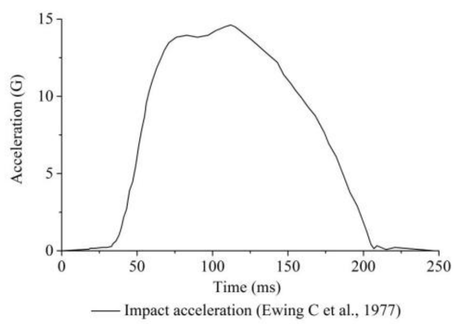


Figure 8. Frontal impact acceleration curve

2.3 Influence of different frontal-impact strength on the cervical spinal cord of passengers

The front article has introduced the establishment and validation of the hybrid dummy model with complete cervical spinal cord, which laid a solid foundation for the next research. When the vehicle was hit by a shock, the degree of damage was caused by different amounts of the crash energy, so this chapter studies the influence of varied intensity of the frontal impact on the cervical spinal cord. The specific injury mechanism about cervical spinal cord is analyzed as well as the effective protection measures are put forward. In this chapter, using the hybrid dummy model has been successfully established, the frontal-impact simulation experiment in low, medium and high intensity is developed. In order to study the muscle effects on kinematic response of Head-Neck Complex in frontal Impact, Fan Li et al.[25] has made impact test at 60 km/h adapted from Wittek A's study[29], they also made a line interpolation from 0 km/h to 60km/h. According to the result of interpolation, low, medium and high intensity of the pre-collision is expressed by 10km/h,30km/h and 50km/h separately. Using the Yaris car FEM developed by George Washington University and United States National Center for collision analysis, Fan Li et al. got three acceleration curves (Figure 9) by three frontal 100%-rigid-wall crash simulations in speeds of 10km/h, 30km/h and 50km/h. These curves were made as input conditions of passenger cabin of Hybrid dummy model in this paper.

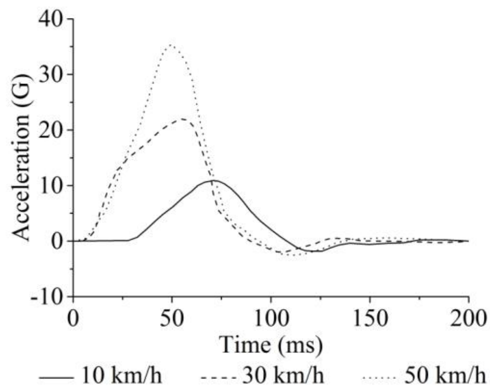


Figure 9. Acceleration curve as inputs of Hybrid FEM model

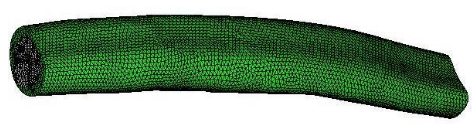
After the frontal impact, the stress at any point of human cervical spinal cord is different along with the time variation. It is obvious that the maximum of stress often causes the most severe damage, so this research focuses on the analysis and discussion of the maximum value of the stress in different regions of the cervical spinal cord. In order to observe the injury severity of different regions of the spinal cord under different impact conditions, the maximal stress of each area was analyzed statistically and the results of the analysis are represented by histograms. Because of the particularity of the physiology and movement of the intervertebral disc, a investigation of spinal cord in different levels was made by distinguishing between vertebral bodies and intervertebral discs. At the same level of the spinal cord, because the physiological function is different in varied region and the material properties of the gray matter and white matter are different, so the gray matter was distinguished from white matter as well as dorsal white matter and ventral white matter.

3 Results

3.1 Cervical Spinal Cord FEM

In this paper, a simple spinal cord FEA model is constructed successfully, including the gray and white matter, as seen in Figure 10(a). Also, a complete 3D FEA model of the cervical spinal cord is constructed successfully, including the gray matter, the white matter, the pia mater, the dura mater and the cerebrospinal fluid, as seen in Figure 10(b).

(a)



(b)

Figure 10. (a) The simplified finite element model of spinal cord; (b) Three-dimensional finite element model of spinal cord

3.2 The Validation of Cervical Spinal Cord FEM

Jianzhong Hu et al.[23] attacked on the spinal cord of rat, the final result is shown in Figure 11 (a). As shown in the image, the blood-vessels on the central region of the rat's spinal cord defects seriously while the peripheral region defects lightly after attacking. Through the stress photograph of the simulation test on the simple spinal cord FEA model, as seen in Figure 11(b), the central and the peripheral region of gray matter of the spinal cord have a larger stress, the region of the white matter has a smaller stress, particularly in the peripheral region. The stress distribution of the simulated experiment accurately reflects the distribution of the severity of spinal cord injury, which is consistent with the study of Jianzhong Hu et al.. The results of tensile test has a contrast with the test result of Maiman et al.[15] and the simulation result of Xinfeng Li et al.[24], as shown in Figure 12. The tensile test of the simple spinal cord FEA model shows the same trend with the result of Maiman et al.[15] and Xinfeng Li et al.[24].

(a) **(b)**

Figure 11. (a) The image of the blood-vessels of the rat's spinal cord; (b) The Cross-section stress photograph of spinal cord FEA model

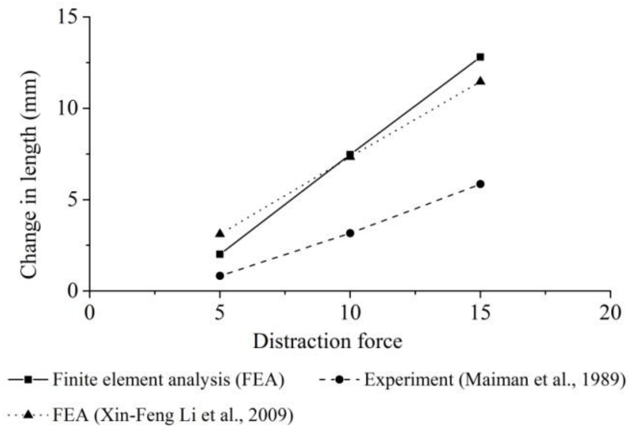
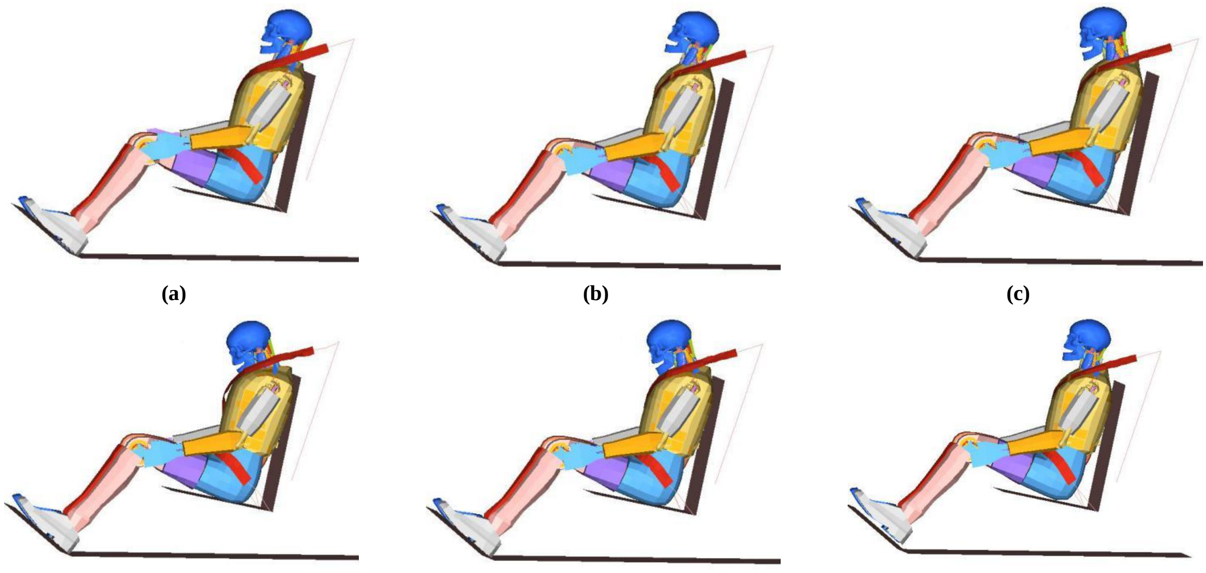


Figure 12. The results of tensile test

3.3 The Validation of Hybrid FEM

This part of article has built a successful hybrid dummy model including cervical spinal cord, vertebral, intervertebral disc, ligaments, muscles and other body structure such as head, trunk and limbs.

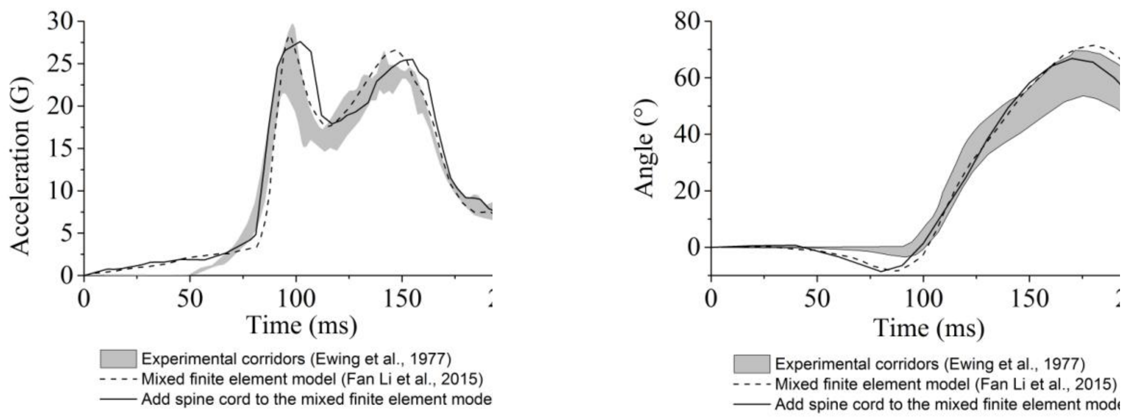
Through the analysis of simulation results, the moving process of the Hybrid dummy model with the spinal cord is basically same as the research of Fan Li et al.[25], this paper makes front-collision simulation test of 30km/h as an example, the Hybrid dummy model's movement process is shown in Figure 13. After the collision, the occupant's neck protrusion decreases until disappears, and then the neck flexion gets to the maximum. Then, the degree of flexion decreases, and gradually returns to the initial state that the neck shows a physiological lordosis again.



(a) (b) (c)

(d) (e) (f)

Figure 13. Hybrid dummy model's movement process during frontal crash. (a) Initial state; (b) Leaning state of body; (c) Forward flexion of the neck; (d) Excessive flexion of neck; (e) Body resilience status; (f) Final state.



(a) (b)

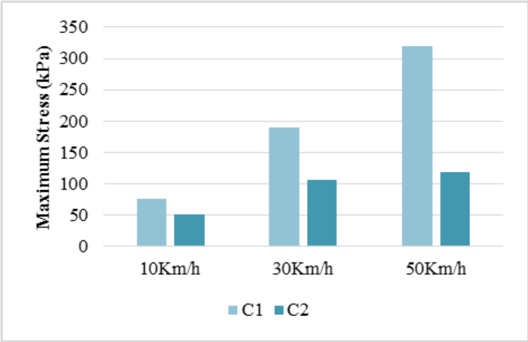
Figure 14. (a) The acceleration curve of head centroid; (b) The angle curve of head rotation.

As is shown in Figure 14, the trend of the kinetic data obtained in the pre-crash verification tests is consistent with the response curve channel of the human body in experiment generally. Most of the time points of response curves fall within the response channel and the value of amplitude was basically equal. In contrast to the experimental results of Fan Li et al., the trend of response curve is basically consistent and the peak value of the acceleration on the head centroid and the peak value of the rotation angle of the head are lower.

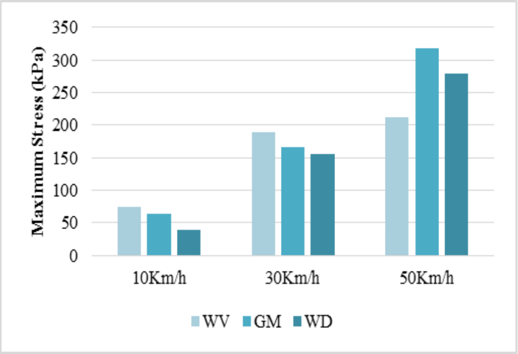
3.4 The injury results of different pre-crash strength

3.4.1 The result of the maximal stress in the upper cervical spinal cord

When the current collision speeds are 10 km/h, 30 km/h and 50km/h, respectively, the maximal stress of the spinal cord at atlas was analyzed as follows: First, the maximal stress of cervical spinal cord at atlas is higher than that of cervical vertebra, and increases with the increase of colliding speed. Second, the maximal stress of cervical spinal cord at atlas is 75.40kPa, 189.70kPa and 318.9kPa when the current collision speeds are 10km/h, 30km/h and 50 km/h, respectively. Correspondingly, the maximal stress of the spinal cord at the axis is 51.13kPa, 106.00kPa and 118.80kPa respectively. The maximal stress of the spinal cord at the atlas is 47.47%, 78.96% and 168.43% higher than that at the axis respectively. Finally, when pre-collision speed is 10 km/h and 30 km/h, the maximal stress of ventral white matter whose value is 75.40kPa and 189.70kPa respectively is higher than that of other parts at the atlas. The stress value of gray matter is centered as 64.66kPa and 167.10kPa respectively, the stress of the dorsal white matter is the lowest as 38.64kPa and 156.10kPa respectively. While pre-collision speed is 50 km/h, the maximum stress value of gray matter is highest (318.90kPa), and dorsal white matter is center as 279.00kPa as well as ventral white matter is the lowest (212.10kPa).Stress analysis of the upper cervical spinal cord at different impact velocities is shown in Figure 15 (a) and the maximal stress in different regions at atlas is shown in Figure 15 (b).



(a)



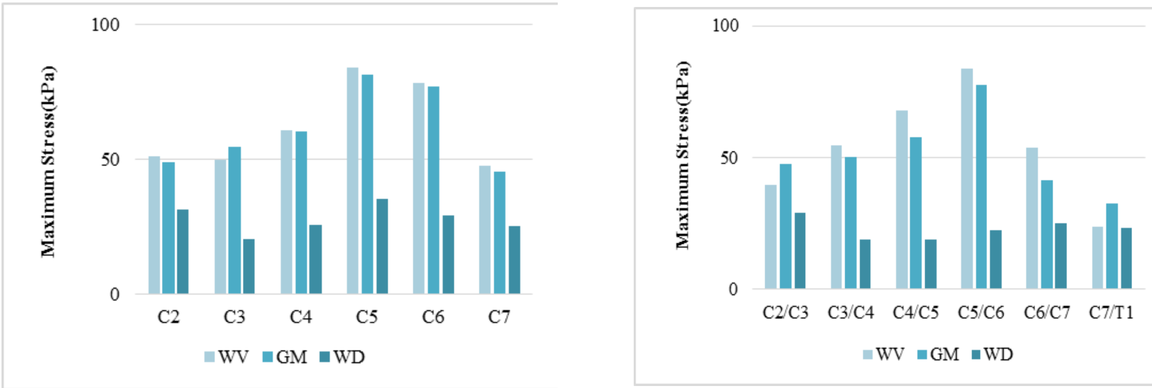
(b)

Figure 15 . (a) Stress of the upper cervical spinal cord at different impact velocities; (b) The maximal stress in different regions at C1. (WV: ventral white matter, GM: gray matter, WD: dorsal white matter)

3.4.2 The result of maximal stress in different regions of spinal cord

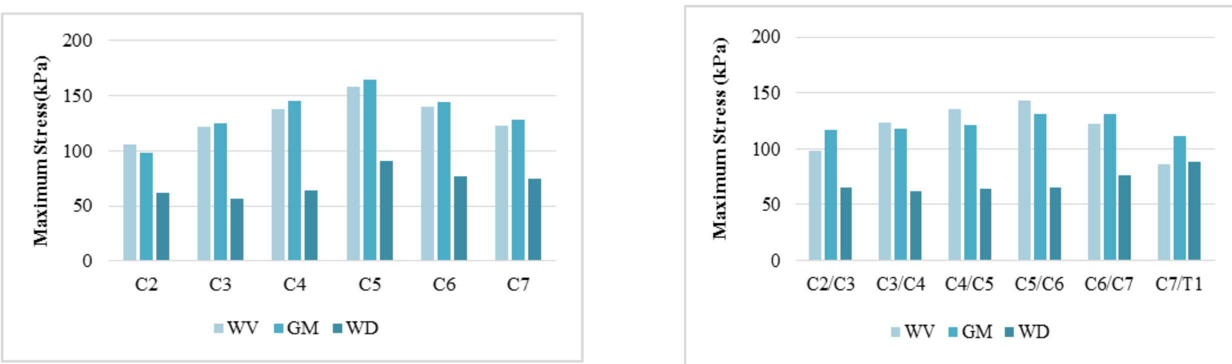
Because of the particularity of the physiology and movement of the intervertebral disc, a investigation of spinal cord in different levels was made by distinguishing between vertebral bodies and intervertebral discs.

Under different front collisions, the general rule of the maximal stress of the spinal cord at each vertebral body level shows as follows: From the vertebral body of the axis down to 7th cervical vertebras, the maximum stress of the spinal cord shows the trend of increasing firstly and then decreasing and the maximal stress all is found at 5th cervical vertebras. There is no significant difference in the maximal stress of the ventral white matter and gray matter at different vertebral bodies, which is significantly higher than that of the dorsal white matter. Compared with the maximal stress of the spinal cord at each vertebral level, from the vertebral disc between the axis and 3rd cervical vertebras down to the vertebral disc between the 7th cervical vertebras and the 1st thoracic vertebrae, the maximal stress of the spinal cord shows the trend of increasing firstly and then decreasing, and the maximal stress is all found at the vertebral disc between the 5th cervical vertebras and the 6th cervical vertebras or at the vertebral disc between the 6th cervical vertebras and the 7th cervical vertebras. The stress of ventral white matter and gray matter at the vertebral disc is higher than that of dorsal white matter except the vertebral disc between the 7th cervical vertebras and the 1st thoracic vertebrae. In general, there is no significant difference in the maximal stress of the ventral white matter and gray matter at the vertebral disc. Specific rules as shown in Figure 16, Figure 17 and Figure 18.



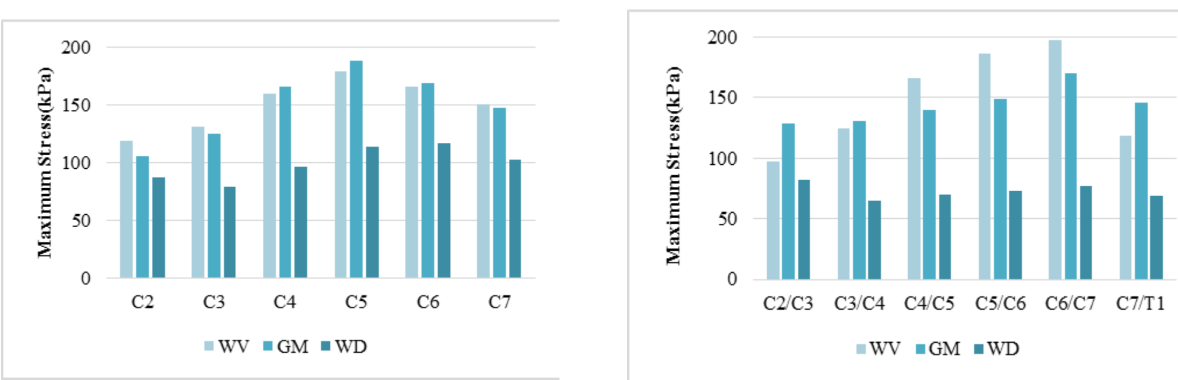
(a) **(b)**

Figure 16. (a) The maximal stress of the spinal cord at vertebral body level in different regions at the speed of the 10km/h; (b) The maximal stress of the spinal cord at intervertebral disc level in different regions at the speed of the 10km/h.



(a) **(b)**

Figure 17. (a) The maximal stress of the spinal cord at vertebral body level in different regions at the speed of the 30km/h (b) The maximal stress of the spinal cord at intervertebral disc level in different regions at the speed of the 30km/h.

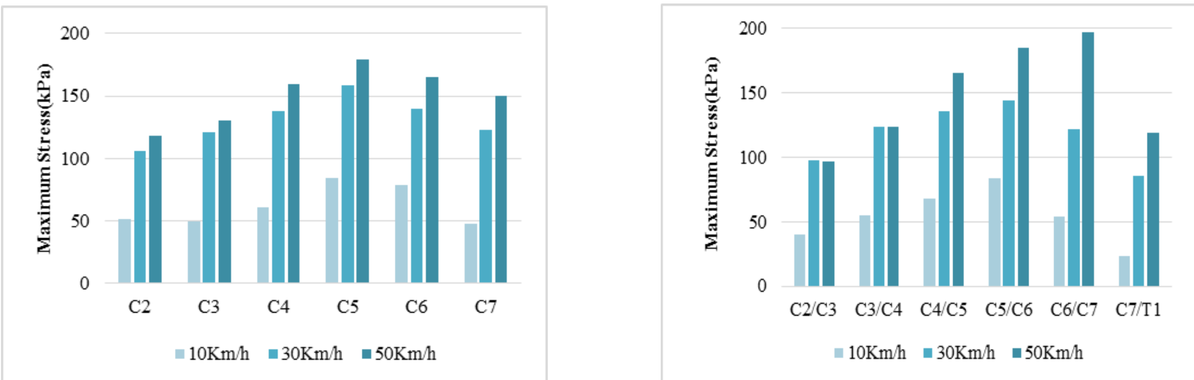


(a) **(b)**

Figure 18. (a) The maximal stress of the spinal cord at vertebral body level in different regions at the speed of the 50km/h (b) The maximal stress of the spinal cord at intervertebral disc level in different regions at the speed of the 50km/h.

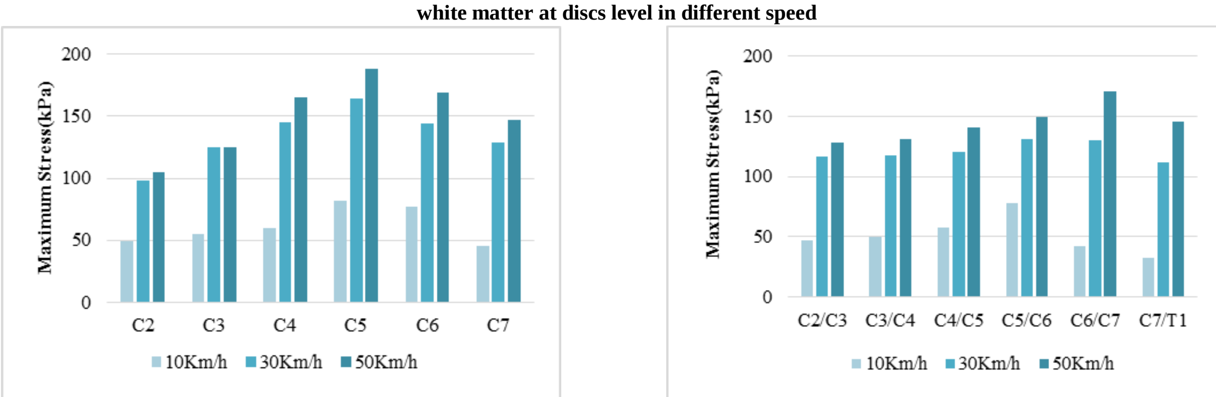
3.4.3 The relationship between maximal stress of spinal cord and the velocity of frontal impact

By study the law of maximal stress at different speeds in several specific regions, the discs and vertebral body are discussed separately, the general rules of vertebral body level are as follows: in addition to the maximal stress of the dorsal white matter in the speed of 50km/h appears in the level of the 6th vertebral body, the maximum of stress in ventral white matter, gray matter and dorsal white matter in speed of 10km/h, 30km/h and 50km/h occurs at the 5th cervical vertebrae. In addition to the gray matter of the cervical spine cord at the 3th cervical vertebrae in the speed of 30km/h and 50km/h, the maximum of stress is equal when the collision occurred, and the maximum of the stress of each vertebral body is highest in the collision speed of 50km/h. The maximum values of stress in the others vertebral bodies is increased with the increase of the velocity of collision. Compared with the vertebral body level, the general rule of the stress maximum of the discs in the different regions of the spinal cord in pre-collision is as follows: in addition to dorsal white matter at the disc between the 1st thoracic vertebrae and the 7th cervical vertebrae, the maximal stress in rest of regions of other discs is found in 50km/h. Except for ventral white matter between the 2nd cervical vertebrae and the 3th cervical vertebrae, and dorsal white matter between the 1st thoracic vertebrae and the 7th cervical vertebrae, the stress of the other regions increases with the increase of the velocity of collision. These results as seen in Figure 19, Figure 20 and Figure 21.



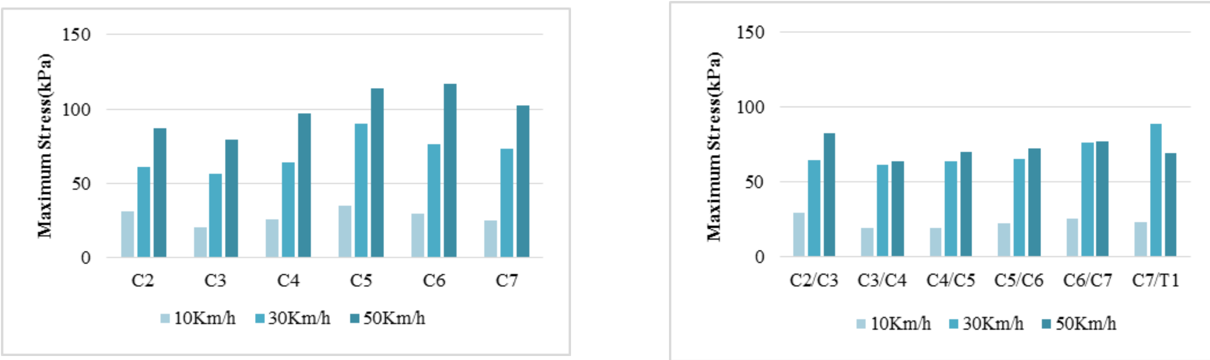
(a) (b)

Figure 19. (a) The maximal stress of ventral white matter at vertebral body level in different speed (b)The maximal stress of ventral white matter at discs level in different speed



(a) (b)

Figure 20. (a) The maximal stress of gray matter at vertebral body level in different speed (b) The maximal stress of gray matter at discs level in different speed



(a) **(b)**

Figure 21. (a) The maximal stress of dorsal white matter at vertebral body level in different speed (b) The maximal stress of dorsal white matter at discs level in different speed

4 Discussion

Since the beginning of twentieth Century, people have been committed to the study of neck injury, because the anatomy of neck is very complex, the mechanism of neck injury is not clear in pre-collision. The researchers put forward some hypotheses about the mechanism of cervical spinal cord injury. Larder et al.[30]found that the critical factor leading to the neck injury is the excessive flexion of the cervical vertebras. Ewing et al.[27, 31]showed that the cervical vertebras exhibited an S-shape after a frontal impact and then the neck was excessively flexed, which could lead to neck injury. In order to study the mechanism of spinal cord, this paper compare the damage degree between the 1st cervical vertebra and the 2nd cervical vertebra. At the same time, the spinal cord at vertebral body level is distinguished from discs level. Under different velocities, the injury of spinal cord in different regions is studied.

From the above results of Figure 15, compared with the lower cervical vertebras, the maximal stress of the spinal cord at the 1st cervical vertebra level is higher than any other cervical vertebra level under different impact speed by 10km/h, 30km/h and 50km/h respectively. On the whole, with the increase of the intensity of the frontal impact, the stress of the spinal cord in the cervical region is increasing continuously. The stress value is higher in the area directly affected by the impact and spreads to other areas, if the spinal cord is affected both sides, the stress would be concentrated in the gray matter. In addition, the stress of cervical spinal cord at the 1st cervical vertebra level is significantly higher than the 2nd cervical vertebra level, which can be inferred that the relative motion of the atlantoaxial joint is the main reason leading to the spinal cord injury at that level.

Once the frontal occurred, the head and neck of occupant is subjected to impact force and inertia to generate forward flexion movement, during this process, spinal cord also produces the corresponding movement, the ventral white matter is more close to the front wall of the spinal canal, at the same time, and the distance between the dorsal white matter and the posterior wall of the vertebral canal is increased. so energies are transferred to the ventral white matter directly, at this time the stress of ventral white matter is increased as well as ventral white matter deforms, and then energies are passed to dorsal white matter which explains why the stress value of dorsal white matter is less than ventral white matter.

From the Figure 19, Figure 20 and Figure 21, when the intensity of the collision was same, the stress at the level of the fifth and sixth cervical vertebrae is higher than that of the other cervical vertebrae. This is because that the lower spinal canal is thinner than the upper spinal canal in the anatomical structure which makes the spinal cord within the spinal canal easier to crash the wall of spinal canal to gain injury, this result is consistent with the clinical case.

Because there is a great difference in physiology between the intervertebral disc and the vertebral body, the injury mechanism of spinal cord at corresponding level is also different. Comparing the maximal stress of spinal cord at vertebral body level with that at discs level, it is shown that the maximal stress of spinal cord at discs level between the 5th vertebral body and 6th vertebral body is higher whether the stress of ventral white matter or that of gray matter which is also caused by anatomical structure of spinal canal. Figure 18 also shows that the maximal stress of ventral white matter at discs level between the 7th vertebral body and 6th vertebral body is higher than that at the 6th or 7th vertebral body level. This phenomenon demonstrates that the high-intensity collisions lead to the damage of the disc, then the posterior longitudinal ligament is compressed which lead to the compression of spinal cord.

5 Conclusions

A Head-neck complex FEM with the cervical spinal cord including gray and white matter, pia and dura mater and cerebrospinal fluid was developed. And the above model has been verified by series of tests. The frontal impact was simulated in different speeds and the maximal stress in different regions of the cervical vertebras was analyzed to reveal the injury mechanism of cervical spinal cord. This paper explains that ventral white matter and gray matter lesions of the cervical spinal cord of the occupant are more serious than the dorsal white matter, and the severity increases with the increase of the intensity of the collision. The stress of cervical spinal cord at atlas is significantly higher than that at axis level, which can be inferred that the relative motion of the atlantoaxial joint is the main reason leading to the spinal cord injury at atlas and axis level. When the intensity of the collision is same, the stress at the fifth and sixth cervical vertebrae level is higher than that of the other cervical vertebrae, this phenomenon is caused by the anatomical structure of spinal canal. The high-intensity collisions lead to the damage of the disc which lead to the compression of spinal cord.

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