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Review of studies on Mechanical Performance of Spinal Cord in Traumatic Injuries

Abstract

Considering the extent of the disability caused by spinal cord injury and the increasing incidence of it, many attempts have been made to understand how this lesion is repaired. Most of the spinal cord injuries are traumatic injuries. The annual incidence of this damage is estimated between 15-40 cases per million people worldwide. Considering the extent of this incident, the need for study of the effects of spinal cord injuries, in particular, in traumatic injuries, is necessary. Due to the ethical and practical difficulties and limitations, as well as the high cost of performing empirical studies on the living and corpse, the use of finite element modeling is a powerful and complementary tool for the study of spinal biomechanics. This method is able to predict how the spinal cord gets injured in different loads and whether one can determine the amount of spinal cord strain and the critical level for spinal cord injuries. Such prediction can play an important role in treating these lesions and improving patients. This study, reviews the previous studies about finite element analysis on the spinal cord. Different aspects of finite element model include methods of its modeling, determination of mechanical properties, loading injury determination of spinal cord have been presented. The results of these studies are compared in order to provide accurate model in future.

Keywords: Spinal Cord Injuries, Spinal Cord, Finite Element Analysis

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Introduction

Spinal cord injuries can be categorized into two types of traumatic and non-traumatic injury. Most of the spinal cord injuries are traumatic, which is usually caused by motorcycle accidents, severe sports injuries and falls. Non-traumatic injuries produce less spinal cord injuries. Spondylolisthesis, Spinal Canal Stenosis, and Vascular problems are some of the non-traumatic spinal cord injury(1). In order to assess the injury accurately, recognizing its actual mechanism is essential. In other words, when the way in which an individual is got hurt, the extent of the injury, the organs and tissues involved in the injury, are determined more precisely, so that the result of the treatment is more rapid and more knowledgeable(2).

The spine is the main component of the human skeletal system at the upper limb. It is divided into cervical, thoracic, lumbar, sacrum and coccyx segments. The main tasks of this part are to support the whole body, as well as to support vital parts of the body, such as the nerves and the spinal cord, which are inside it. The spinal cord located inside the spine is one of the main components of the central nervous system of vertebrates, which is responsible for the transmission of sensory and motor signals between the brain and other areas of the body. The spinal cord and spine can be exposed to traumatic and non-traumatic injuries. The spinal cord traumatic injury causes a wide range of injury mechanisms. Some injury mechanisms can lead to spinal cord injury. Spinal cord traumatic injury occurs when the white matter of the spinal cord is exposed to a sudden trauma or that the axons of white matter or grey matter are injured.

The mechanical forces that cause the injury are a combination of compressive, tensile, shear and torsional loads that ultimately result in disability of a person by interrupting the connection of the neural cells that do not have a definite restorative treatment. The spinal cord injury is variable in severity and can range from minor injuries such as flexion, strain with vertebral displacement, bleeding, soreness, and contusion to spinal cord rupture(3). Three of the most commonly reported traumatic injuries are contusion, dislocation, and distraction.

Understanding the physiology of spinal cord alteration is very important for obtaining the threshold of injury. Most empirical studies face serious constraints, so using analytical methods can work in this regard. One of these methods is the finite element method. An important point is that number of this kind of research in this field is limited and most studies have investigated the injuries to the spine vertebrae, while the most serious injuries are applied to the spinal cord during external load that can lead to paralysis of the limbs. Therefore, accurate examination of spinal cord function in injuries is essential. Given that in finite element studies, not all of the complexity of the original model is considered, existing models need to be compared and evaluated in order to be a light for future studies. This study introduces researches carried out in this field. The purpose of this study is to compare numerical studies and finite element models in previous studies and to evaluate their results in order to provide more accurate modeling in the future.

In The following, the review of the empirical research on the mechanical behavior of the spinal cord to different loading, and in the next section, numerical studies and modeling in two sections of human modeling and animal modeling are considered. In the end, the outcome of the reviews will be expressed.

Empirical Studies

Limited experimental studies have been performed on human and animal spinal cord tissue. These studies have been carried out to better understand the mechanism of spinal cord injury or to find out the mechanical properties of the spinal cord. The results of experiments performed on animal specimens are presented in Table 1.

One of the first researches in this field was carried out by Allen et al. (1911)(4). In this research, contusion injury has been analyzed by testing on the spinal cord of the dog. In subsequent studies, Hung et al. (1981) and (1982)(6) examined the contusion injury by performing a test on the spinal cord of cat and obtained the elasticity modulus of the spinal cord of the cat by applying the axial tensile and compressive load. In 1981 Hung and Chang(7) examined the spinal cord of the dog under unidirectional load and examined its behavior and elicited results of the elasticity modulus of the spinal cord. In 1989, Maiman et al.(8), with the purpose of examining the mechanical behavior of the cat spinal cord, applied it under deviation load and concluded that by applying this load, the amount of stress in the white matter of the spinal cord of cat is greater than that of the grey matter. Jones et al. (2008) examined the effect of the cerebrospinal fluid on the bovine spinal cord and examined the effect of this fluid on spinal cord protection, and found that this fluid has a significant role in protecting the spinal cord. In 2004, Ozawa et al.(10) performed tests on the rabbit spinal cord to obtain mechanical properties. Fiford et al. (2004) examined the spinal cord in a dislocated load and found that axonal injury was greater in the white matter. Fiford and Bilston (2005) conducted experiments on 6 specimens of rat spinal cord in order to find the mechanical properties and reported these properties in the form of viscoelastic according to Table 2. Choo et al. (2009)(13) tested the rat spinal cord injury in three cases, distraction, contusion, and dislocation and checked the amount of axonal injury in each injury, by measuring the change in the length of the Ranvier nodes. In 2009, Clarke et al.(14) conducted in vitro experiments on 8 specimens of rat spinal cord to achieve neural properties and reported the viscoelastic spinal cord tissue properties according to Table 2. Oakland et al. (2006)(15) examined the response of the bovine spinal cord to a unidirectional load in order to investigate the mechanical response, and reported the elasticity modulus of the spinal cord tissue of bovine. Polack et al. (2014)(16), with the purpose of examining the biomechanical structure of the dentate ligaments in the cervical spine, performed experiments on spinal cord tissue and identified the role of these ligaments in protecting the spinal cord from traumatic injuries. Meanwhile, most of the experiments are presenting the properties of the spinal cord uniformly, and there is no difference between the gray and the white matter tissues, but in the results of the experiments conducted by Ichihara et al., 2001(17), the properties of the white and gray matters were presented separately by performing tests on the bovine spinal cord, and it has finally been inferred that the elasticity modulus of the white matter is larger than its value in the grey matter.

Furthermore, limited experiments have been performed on the human spinal cord in the form of in vitro, including the Bilston and Thibault research in 1995(18) to find mechanical properties of the cervical region. Also, Yuan et al. (1998)(19) examined the human spinal cord under bending load and examined how the spinal cord is deformed and displaced. Ko et al. (2004)(20) conducted an in vitro experiments on human spinal cord injuries in order to determine the dimensions and parameters, including the diameter and the volume of each part of the spinal cord (cervical-thoracic-lumbar). In 2017, Karimi et al.(21) put 24 specimens of the human fresh spinal cord tissues under compressive load at different rates of strain and reported linear elastic and hyperelastic properties of the spinal cord. The elasticity modulus of this tissue is reported to be about 40.12 kPa and the fracture stress is 62.26 kPa.

Table 1: The results of some experimental studies on animal specimens in order to determine the mechanical properties of spinal cord tissue

Type of experiment	Number of specimens	Young's Module	Type of specimen	Reference of experiments
In vivo	3	0.26 (MPa)	cat	Hung et al. (1981) (5)
In vivo	10	0.215-0.295 (MPa)	dog	Hung and Chang (1981) (7)
In vivo	4	0.4 (MPa)	cat	Hung et al. (1982) (6)
In vitro	3	0.166 (MPa) white matter 0.025 (MPa) grey matter	cow	Ichihara et al., (2001) (17)
In vitro	9	0.05-0.16 (MPa) These values are reported for Pia Mater	rabbit	Ozawa et al. (10)
In vitro	6	Properties have been reported as viscoelastic, see Table 2	rat	Fiford and Bilston (2005) (12)
In vitro	1	1.19 (MPa)	cow	Oakland et al. (2006) (15)
In vitro	8	Properties have been reported as viscoelastic, see Table 2	rat	Clarke et al. (2009) (14)
In vitro	98	1.95 (MPa)	pig	Polack et al. (2014) (16)

Table 2. Viscoelastic properties of the spinal cord derived from experimental experiments

Reference of experiments	A	B	β	G_0	G_1	τ_1	G_2	τ_2	G_2	τ_3
Fiford and Bilston (2005) (12)	0.0288	21.22	1.3418	0.7913	0.0190	0.7103	0.0890	0.0216	0.1001	0.0027
Clarke et al. (2009) (14)	0.0081	16.75	0	0.5123	0.0142	1000	0.2894	0.0121	0.1841	0.2736

In the explanation of the constants obtained in Table 2, equations 1 to 5 are introduced. In fact, Fiford and Bilston(12) and Clarke et al. (14) have used a nonlinear viscoelastic model. The time-dependent stress is calculated according to Equation (1). In these relations, A and B are the parameters of matter, ϵ is strain rate and $G(\epsilon, t)$ is the reduced relaxation function.

(1)	$\sigma(t) = \int_{-\infty}^{t} \frac{\partial}{\partial \epsilon}(Y[\epsilon(\tau), t-\tau]\dot{\epsilon}(\tau)d\tau$
(2)	$Y(\epsilon, t) = \sigma^{e}(\epsilon) * G(\epsilon, t)$
(3)	$\sigma^{e}(\epsilon) = A(B^{\epsilon} - 1)$
(4)	$G(\epsilon, t) = G_0 + (1 + \beta\dot{\epsilon})[G_1 e^{-\tau_1 t} + G_2 e^{-\tau_2 t} + G_3 e^{-\tau_3 t}]$
(5)	$\epsilon(t) = \begin{cases} \dot{\epsilon}_0 t & for\ 0 < t < t_0 \\ \dot{\epsilon}_0 t_0 & for\ t \geq t_0 \end{cases}$

Numerical studies and modeling

• Human models

As previously mentioned, in recent years, computational studies (finite element analysis) have been developed in this field to better understand how the biomechanics of the spinal cord and spine are addressed, including the research carried out in this field by Bilston et al. (1998) (22). Bilston et al. developed a 2D model of the brain, spine, and spinal cord (posterior and anterior planes) to analyze brain and cervical section of the spine and spinal cord. This modeling included the brain, cervical vertebrae, cervical spinal cord tissues, and cerebrospinal fluid. In this study, the nerves and ligaments are not modeled. In this research, the vertebrae are rigidly modeled, with the justification that their deformation in comparison to the spinal cord is negligible. The cerebrospinal fluid is considered as a viscous fluid with viscosities around water. The properties of the spinal cord have been extracted from the Bilston and Thibault research (18) and the brain tissue properties of the Galford JE and McElhaney research (23). In the study of Bilston et al.(22), behavior and alteration of the cervical spinal cord in tensile and compressive loading is examined. In order to validate the modeling, the results were compared with the results of experiments conducted on the physical model created by Bilston and Thibault in 1997(24). In this comparison, the strain is created and the degree of displacement of the spine vertebrae is compared with the finite element modeling (in tensile and compressive loading) with the values created in the physical model, and the results are relatively consistent with the approximation.

In another study, Scifert et al. (2002)(25) considering that the cervical spinal cord and spine injury was more likely in the accidents, intended to examine these sections (26). The probability of injury in different sections is listed in Table 3.

Table 3. The possibility of injury in different parts of the spine and spinal cord

Position of injury	Probability of injury
The cervical section between vertebrae of C1-C2	11%
The cervical section between vertebrae of C3-C7	51%
The thoracic section between vertebrae of T1-T10	14%
The lumbar section between vertebrae of T2-T11	20%
The sacrum section between vertebrae of L3-S3	4%

In the research of Scifert al., a 3D model of the spine and spinal cord of the C5-C6 vertebrae was modeled using MRI images in Abaqus software. Also, nerve fibers, dentate ligaments, Dura matter, cerebrospinal fluid, white and gray matter are considered. The properties of these sections have been extracted using the research of Yuan et al. (19), Van et al.(27) and Moroney et al.(28), and the structural model of all sections are considered as linear elastic. It should be noted that the study of Van et al. in 1981(27) was carried out to investigate the mechanical properties of human Dura mater. In this research, the model is under compressive and bending loads. After applying the load, the strain rate is calculated at the surface of the white and gray matter. The results of this study indicate that in compressive loading, the strain rate in the posterior section of the spinal cord is greater than the anterior section, and therefore the posterior section is more vulnerable. Also, the maximum von Mises stress in the spinal cord during bending loading is about 4.09 MPa. In order to validate the model, the results such as strain rate in the spinal cord and Dura matter are compared with the results of the tests of Yuan et al.(19), which are close to the experimental results, but unlike our prediction in modeling, in experimental experiments with applying the bending loading, the strain rate in the posterior section of the spinal cord is less than the anterior section.

In another study Greaves et al. (2008)(29) modeled the 3D model of the spinal cord and spine in the C5 to C6 sections and examined several different injury mechanisms on this model. The purpose of this study was to evaluate and compare the distribution of strain in the spinal cord for different mechanisms of injury, such as contusion, distraction, and dislocation. The properties used in this modeling are extracted from other empirical and numerical studies and the structural model of all sections is considered as linear elastic. In this study, the maximum von Mises stress in dislocation, distraction and contusion injuries was 0.32, 0.1 and 0.37 MPa, respectively, and the maximum shear strain was 0.03, 0.07, and 0.11, respectively. Finally, in order to validate the modeling in contusion injury, the results of the human finite element model are compared with the results of the experiments performed by Hung et al. on the cat spinal cord(6, 30), which is well matched. This validation is based on the justification that the human and animal spinal cord is close together. The modeling results are compared with the results of animal testing by Maiman et al.(8). This comparison shows that the modeling results are very well suited to the test results. However, the results of the modeling of dislocation injury have not been compared with any experimental data.

In another study by Czyz et al. (2008)(31) a model of a 3D finite element of the cervical spine of a young man was created using MRI images and simulated in the Ansys software environment. This modeling includes white, gray, Pia, and Dura matter and dentate ligaments. The properties of different sections in this modeling are extracted from other empirical and numerical studies and the structural model is linear elastic. The purpose of this study was to obtain the relationship between spinal cord transformation in a finite element model and actual spinal cord images. This model is under bending loading and according to the results obtained from this study, the most vulnerable section in the spinal cord is the upper edge of the white matter, as well as the anterior and the central section of the gray matter. In order to validate, the results of this modeling have been compared and evaluated with MRI images of a large number of patients.

In 2012, Ben-Hatira et al.(32) modeled a 3D model including vertebrae L1 to L5, four discs, ligaments, and spinal cord of this section of the spine. In this modeling, the vertebrae are modeled elastically and orthotropically, and the rest of the sections, linearly. In this study, the applied loads were compressive, lateral bending and a combination of these two types of loading onto the model and the values of von Mises stress for the different sections of the spinal cord were calculated. Finally, by analyzing the results, it has been stated that in compressive loading, the greatest amount of tension on the spinal cord was applied on the vertebrae of L1, and the most vulnerable section of the spinal cord is the posterior section in terms of cross-sectional view. Also, in combination loading, the tension level created in the vertebrae is much higher than the spinal cord and discs.

Yan et al. (2012)(33) investigated the mechanical response of the spinal cord in the thoracic region, developed the L1-T12 section by 3D modeling of the Ansys software, which included the white, gray, Dura and Pia matter. Properties used in this modeling have been extracted from other studies. The structural model of the white, gray, and pia matter are considered to be viscoelastic and also the linear elastic model is considered for Dura matter. The model is applied to two axial tensile loading (at a strain rate of 0.048, 0.120, 0.225) and contusion injury and the results of axial loading are compared with the results of the Bilston et al. test (18) and observed that all the strain rates are completely consistent. Also, the results of modeling in contusion injury were compared with the finite element modeling results of Greaves et al.(29) and Hung and et al.(6,30). With respect to this comparison, the results of the recent finite element model are much better consistent, in comparison with the finite element model of Greaves et al. (29), with the results of experiments of Hung and et al. (6,30), and thus more reliable.

In 2016, Fradet et al.(34) followed two objectives by creating a 3D model of the spinal cord. The first objective is to investigate the effect of cerebrospinal fluid on the biomechanical response of the spinal cord and the second objective is to investigate the effect of thickness alteration of the sub-arachnoid matter on the mechanical response of the spinal cord. In this research, four modeling were performed so that the first model only includes white and gray matters. The second model includes white, gray, Dura and Pia Matters. The third model consists of white, gray, Dura, Pia matters, and cerebrospinal fluid. The fourth model is similar to the third model in terms of constituent sections and the only difference is the thickness of the sub-arachnoid matter. The four modeling are carried out by three knockers with three different cross-sections under an impact load (contusion injury). This loading has been applied to the model at the L1 to T6 vertebrae and accordingly the results have been analyzed. Finally, the results obtained from this study are that the applied load on the spinal cord in the lumbar section is less than that of the thoracic section, and it was shown that during the contusion injury, the maximum von Mises stress in the gray and white matter is about 0.5 MPa and 0.375 MPa respectively. It was also observed that the cerebrospinal fluid in the spinal cord protects against trauma and that the thickness of the sub-arachnoid matter has a threshold that, if it becomes thinner, the protection of cerebrospinal fluid from the spinal cord is not well maintained. To validate the results, they are compared with the results of the experiments conducted by Jones et al. (9).

Czyz et al. (2016) (35) conducted a study based on a finite element model of the spinal cord of 28 patients in order to achieve critical stress and strain rates in spinal cord traumatic injury. In this study, a 3D model of the spinal cord was constructed consisting of Dura, Pia matters, and dentate ligaments and the boundary conditions were applied for each case separately. Also, bending loading is applied to the model in all cases. According to this study, there is no correlation between age, gender and injury level with stress and strain values along the spinal cord, and the critical stress and strain values were reported to be about 8.1 kPa and 0.0117, respectively.

Duan et al. (2018)(36) presented 3D finite element model consisting of white, gray matter, Pia matter, and cerebrospinal fluid from the cervical vertebrae section, between the 2nd and 7th vertebrae to investigate the biomechanics of the spinal cord during the contusion injury. Three impact masses of 7 grams, but with different cross-sections and at different initial velocity, have been knocked in order to cause contusion injury in the modeling. By examining the results of this study, with increasing initial velocity of impact, the percentage reduction of cross-sectional area increases. Also, the maximum von Mises stress in the spinal cord is 5 to 7 kPa, 42 to 54 kPa and 240 to 320 kPa, respectively, for the cases with an initial velocity of 1.5, 3.5 and 6 m / s, also the percentage reduction in cross-sectional area of spinal cord in these three cases are 9.3% to 12.3%, 30%, and 50% respectively. In 2019, Biglari et al. (37) aimed to determine the tension and how the shape of the spinal cord transforms during the contusion injury, created a 3D finite element model from the thoracic section of the spinal cord and applied a traumatic injury at three angles, 0, 30 and 45 degrees. It is observed that the maximum amount of von Mises stress was made in a state where the angle of knocker was zero and the maximum stress was about 0.13 MPa. Also, the highest amount of strain was made at this angle and the maximum deformation, in this case, was about 1.42 mm.

• Animal modeling

Modeling of the spinal cord was carried out to determine spinal cord injury of animals. Among the research by Russell in 2012 (38), a 3D model of the cervical spine of the rat was created using MRI images, and this model was subjected to three contusion (at two different velocities), dislocation and distraction injury. In order to validate, the results of modeling in contusion injury have been compared with the results of Maikos et al. (39) and the results of modeling in dislocation and distraction injury with the results of the research by Choo et al.(13). In two dislocation and contusion injuries the results had good consistency, however, there is a difference between the modeling and the experimental results in distraction injury, so that the results are not valid.

In Hunter's research (2016) (40) a 3D model of the brain, spinal cord and cervical spinal cord of rat was created and this model was under dislocation loading and the results were compared with the results of the test by Choo et al. (13). It's been observed that the maximum strain in the spinal cord section was created between the cervical vertebrae 4 and 5, and this strain was about 0.4.

In 2016, Sparrey et al. (41) developed a spinal cord model of a nonhuman mammal prepared for contusion loading. They examined the effect of displacement, direction, and angle of impact. In this study, the angle and direction of impact strongly affect the severity of spinal cord injury.

Conclusion

Reviewing research in the field of mechanical behavior of the spinal cord against traumatic injuries can indirectly influence the provision of strategies for treating patients with spinal cord injury. The studies in this field are mainly carried out in the form of finite element modeling and the behavior of spinal cord in different loading has been investigated. A review of the research has shown that the differences in modeling are mainly in the modeled sections and properties that are considered for different sections. In each modeling, part of the structure and parts of the spinal cord are included. Naturally, the more detailed the modeling is, the more accurate the results will be. It is also observed that the behavior of the spinal cord is closer to the viscoelastic material. Therefore, modeling that considers the mechanical properties of the spinal cord as viscoelastic is more predictive of the spinal cord behavior. In future studies, spinal cord behavior can be better predicted by refining the modeling and considering more details of the spinal cord structure. Also, by changing the properties of the spinal cord, its effect on the distribution of stress and strain is considered.

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