Analysis of the Effects of Trauma on the Biomechanical Response of The Cervical Spine Based on the Finite Element Modeling

Abstract

Background: Cervical spine injuries often cause disability and adversely affect the overall performance and quality of life. Therefore, understanding the damage and dysfunction of the cervical spine and biomechanical response to external stimuli is of paramount importance. Finite element (FE) modeling can help researchers to access the internal stresses and strains in bones, ligaments, and soft tissues. The present study aimed to compare the biomechanical behavior of the cervical spine before and after trauma.

Methods: In this study, we developed a healthy model along with two different traumatic injuries of the cervical spine modeled using the FE method. The results of the models were compared under static loading.

Results: We estimated and evaluated three parameters of intervertebral rotation, facet joint force, and intradiscal pressure by considering follower load. The results of the mentioned parameters were evaluated in the two traumatic injury models, as well as the healthy model in all flexion, extension, lateral bending, and axial rotation movements at all levels.

Conclusion: According to the findings of the current study, trauma modeling caused changes in the biomechanical behavior of the model, including decreased range of motion in the traumatic injury models, reduced intradiscal pressure, and increased facet joint force. This structural disruption in this complex system caused abnormal response in different movements. Our results showed that the lack of improvement in the biomechanical response of the model would cause spinal instability and could augment the probability of injuries in different segments of the lower cervical spine in long term.

Keywords: Trauma, Biomechanical phenomena, Cervical spine, Range of motion, Movement

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Introduction

The cervical spine has the widest range of motion compared to the other levels of the spinal system. In addition, the main role of the cervical spine is to support and promote the movement of the head and neck and prevent intervertebral joint disorders (1). Functional movement of the cervical spine is achieved by the cervical intervertebral discs (2). The cervical spine can undergo flexion, extension, compression, and rotation, each of which has a primary motion. However, the applied force will be much stronger when the forces are used in combination. Therefore, understanding these forces and their combination allows physicians to extract the pattern of intervertebral joint disorders (3). In general, intervertebral joint disorders cause inability and negatively affect the overall performance and the quality of the life in individuals (4). Clinical studies have shown that lower cervical SCI (C_3-C_7) accounts for approximately two-thirds of cervical fractures and three-quarters of cervical dislocations (5).

Injuries are one of the most important causes of mortality and disability in the first four decades of life. Injuries are rising with the growth in the world population. In addition, cervical spine injuries are causing serious health and economic challenges in modern societies globally (6).

In Iran, injuries are the second leading cause of mortality following cardiovascular diseases. Moreover, they are the primary cause of the loss of life years [7]. While cervical spine injuries account for only 2%-3% of patients with blunt traumatic injuries, they are extremely important due to the high mortality rate and associated complications [7]. Some of the causes of cervical neck injuries include traffic accidents, falls, violence, quarrel, or sports-related injuries [7]. Cervical spine injuries caused by a blow to the head or car accidents may have diverse intensities from minor (twisted/stretched) to moderate (lumbar disc disease) or serious and more severe (fracture, dislocation, and spinal injury) [8]. The human cervical spine is one of the most challenging areas for biomechanical modeling due to its complex musculoskeletal structure [9]. Finite element modeling (FEM) can help researchers to access the internal stresses and strains in bones, ligaments, and soft tissues. Furthermore, it can be widely used for spinal biomechanics research. It can also facilitate the diagnosis, treatment, and prevention of cervical spine injuries [10].

The present study aimed to evaluate the biomechanical behavior of the cervical spine before and after trauma. In addition, the FEM was used to facilitate the diagnosis, treatment, and prevention of cervical spine injuries leading to improved surgical standards and reduced complications in these patients.

Methods

1.1.Model Design

The current study focused on designing a model of the cervical spine with different injuries. First, the approximate geometry should be determined to generate the primary model of the vertebrae and discs. MIMICS software was used to implement the process, and the radiography images of a healthy person from lateral and anterior-posterior (AP) angles were entered into the software. Ultimately, distinct geometrical parameters were calculated using the MIMICS measurement tool. To design cervical spine segments, two CATIA and EXCEL software and their relationship were applied following extracting the sizes from MIMICS software to generate vertebrae based on their anatomy, which includes 10% compact and 90% spongy types. Hyper Mesh and Lamina are the best software for designing intervertebral discs and ligaments at the lowest possible cost. Notably, all parts of a vertebra are considered to have dense bone, except for 90% of the vertebral body. Overall, 14 independent parameters were used in this design, and the vertebral body was designed as a cylinder with an elliptical cross-section defined by only three parameters. In addition, the posterior part of the vertebra was designed utilizing three parameters of the length of Lamina, distance from the middle of foramina to the middle of the vertebral body, and the sum of the small radius of the body and the length of the lamina.

1.1.1.Design of a Model with Traumatic Injury

A considerable percentage of damage to the fifth cervical vertebra was reported in previous studies. Therefore, to design a model of the traumatic injury to the lower cervical spine, trauma simulation was carried out in the designed model by changing C_5-C_6 intervertebral disc parameters. Moreover, the parameters of spondylolisthesis were altered, and the vertebrae of the cervical spine were displaced at this segment. According to the collected data, fracture rarely occurs at the C_5 segment. Data shows that 12.8% of the total fractures are attributed to C_5 fractures. Meanwhile, dislocation and displacement due to injury are mostly observed in the C_5-C_6 spinal motion segment (19.3%) [7]. Furthermore, other studies have reported damage to the spine caused by trauma that led to spondylolisthesis and the displacement of the vertebra (76.2%) [7]. Therefore, concerning the data collected and trauma prevalence in the cervical spine, simulation was carried out in a pre-developed CATIA model generated by the displacement of the vertebra and decrease in disc height in the cervical spine of a healthy model. The C_5 segment was displaced 10 mm and the height of the C_5-C_6 segment was reduced by 20% in order to model spondylolisthesis due to a blow (subluxation), facet dislocation, and displacement. In a model of traumatic injury, in addition to injury to vertebra and disc displacement, the soft tissue and ligaments are damaged. Researches demonstrated that the most damage is injuries to ligaments in the same and adjacent segments. This includes damage to the upper or lower segment or both segments simultaneously (11). Injury to an adjacent ligament is the most common type of injury occurring following trauma to the soft tissue. In previous studies, 33% of people with traumatic injuries suffered from a ligament tear in the adjacent segment, and 10% of cases had damage and tear in the ligament of the same segment. Moreover, most damages are related to the C_5-C_6 segment (11). The current study models and evaluates the results of these two important segments.

1.1.1.Adjacent Level Ligamentous Injury Modeling

The model entailed an injury to the spinal cord at the C_5-C_6 level with spondylolisthesis, as well as disc and vertebra displacement in this segment. In addition, damage was observed in the upper and lower adjacent ligaments. The damage could be found in the upper adjacent level (i.e., C_3-C_4) and lower adjacent level (i.e., C_6-C_7). Damage and tear were noted in posterior longitudinal ligaments, ligamentum flavum, capsular ligaments, supraspinous ligaments, and interspinous ligaments.Figure 1 shows modeling by eliminating these ligaments (Figure 1).

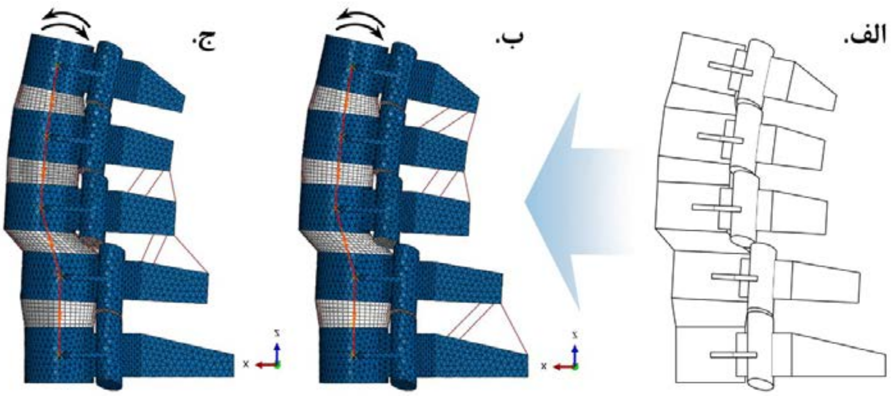

Figure 1. A Model of traumatic injury; A) model designed in CATIA, B) finite element model with ligament tear at the level suffering from a traumatic injury, C) finite element model with ligament tear at the adjacent levels

Table 1. Mechanical features of finite element models

Cervical Spine Elements	* Mechanical Properties	**Cross-section	**Reference**
Dense bone of the vertebral body	V=0.3, E=10000	-	**[12]**
Spongy bone of the vertebral body	V=0.2, E=100	-	**[13]**
Fibrous region of the disc	C10=0.56 C01=0.14 D1=0.45	-	**[6]**
The nucleus of the intervertebral disc	C10=0.12 C01=0.09 D1=0.49	-	**[6]**
Collagen fibers	E=1, v=0.3	-	**[14]**
Facets	E=10, v=0.4	-	**[13]**
Anterior longitudinal ligament	E=10, v=0.3	1	**[15][16]**
posterior longitudinal ligaments	E=10, v=0.3	1	**[15][16]**
Ligamentum flavum	E=1.5, v=0.3	0.4	**[15][16]**
Interspinous ligaments	E=1.5, v=0.3	3	**[15][16]**
Supraspinous ligaments	E=1.5, v=0.3	5	**[16]**
Capsular ligaments	E=10, v=0.3	1.2	**[15][16]**

*E= Elastic modulus based on MPa; **Cross-section based on mm^2; v= Poisson's ratio;
(C10, C01, D1= Mooney-Rivlin hyperelastic model parameters)

1.1.2. Ligament Tear Modeling at the **injured** Level

According to the results of previous studies, there is a significant probability of ligament tear at the same level suffering from damage and trauma [11]. Trauma at the C_5-C_6 level leads to the tear and damage of longitudinal posterior ligaments, ligamentum flavum, capsular ligaments, supraspinous ligaments, and interspinous ligaments. Figure 1 indicates modeling by eliminating these ligaments in the same segment (Figure 1).

1.2.Specification of Mechanical Properties

In this study, ABAQUS was applied to specify mechanical properties. In this respect, the mechanical features of the dense and spongy regions of bones and ligaments were all considered isotropic elastic. In addition, the two parts of the fibrous region and the nucleus of the intervertebral disc were regarded as Mooney-Rivlin Hyperelastic model with three fixed parameters (Table 1).

1.2.Loading Condition

In the present research, the follower load method was used to simulate the head weight force and passive muscle forces in the axial direction of the spine [17].

Results

First, the results of the healthy model were evaluated and confirmed. In order to validate the healthy model, the findings of intervertebral rotation due to the application of net torque in each segment were separately validated and compared with the results of the intervertebral rotation of the in vitro experiments performed by Panjabi and Wheeldon [18, 19]. The model of the cervical spine with traumatic injury was examined in flexion, extension, lateral bending, and axial rotation movements under 1 Nm torque. Furthermore, three parameters of vertebral rotation, facet force, and intradiscal pressure were measured and assessed considering the follower load. Moreover, the two traumatic injury and healthy models were assessed and compared in terms of vertebral rotation results in flexion, extension, lateral bending, and axial rotation at all C_3-C_7 levels. On the other hand, facet force was evaluated in all joints and all levels of the cervical spine, and intradiscal pressure was assessed at C_3-C_7 levels in the traumatic injury and healthy models (Figure 4). According to our results, the intervertebral rotation decreased in different movements of axial rotation, extension, and lateral bending in all segments, but not in flexion. However, the results showed a variety of intervertebral rotation behaviors. In this movement, a 13.79% increase was found in the intervertebral rotation angle in the traumatic injury model, which included the tear of adjacent ligaments, compared to the healthy model. On the other hand, there was a 9.03% decline in the model of traumatic injury with ligament injuries at the same level. Similar to other movements, there was a reduction of intervertebral rotation angle at the C_4-C_5 level due to torque loading. In the flexion movement and at the C_5-C_6 level, a 55.92% elevation in the traumatic injury model with ligament damage and a 45.48% augmentation in the traumatic injury model with the tear of the adjacent ligaments were predicted, in comparison with the healthy model. At the C_6-C_7 level, there was a 13.08% and 7.52% raise in the traumatic injury model with an adjacent ligament tear and ligament tear at the same level, respectively, compared to the control model. However, damage and tear of posterior ligaments at the same and adjacent levels could justify the higher results of intervertebral rotation in flexion in traumatic injury models, compared to the healthy models. Trauma complicates the structure of the spine resulting in a reduced range of motion at all levels in different movements of axial rotation, extension, and lateral flexion (Figure 2).

In this section, we evaluate the results obtained from intradiscal pressure in all movements. According to our findings, intradiscal rotation diminished in axial rotation, extension, and side bending movements at all distinct levels of the model under similar loading conditions. However, variable results were obtained regarding the flexion movement, in which we observed a 2.28%

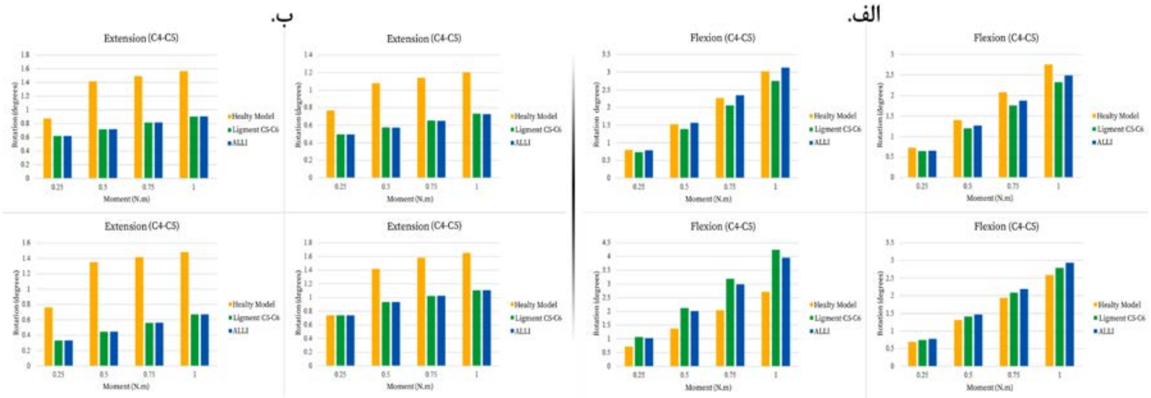

Figure 2: Results of intervertebral rotation in models with trauma and its comparison with healthy model a) Results of intervertebral rotation of all surfaces in flexion motion b) Results of intervertebral rotation of all surfaces in extension

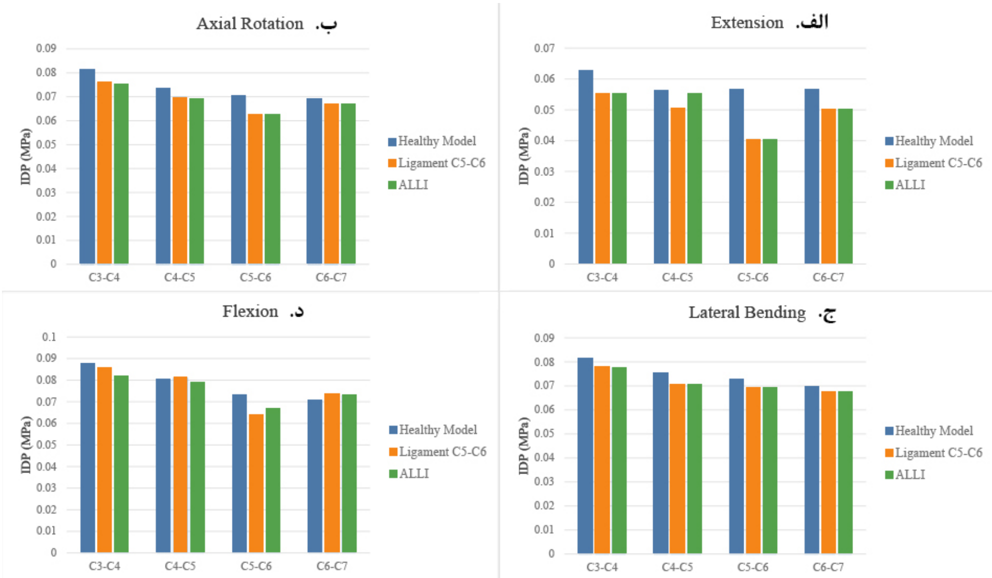

Figure 3. Results of intradiscal pressure in different movements of traumatic injury and healthy models; A) extension, B) axial rotation, C) lateral bending, D) flexion

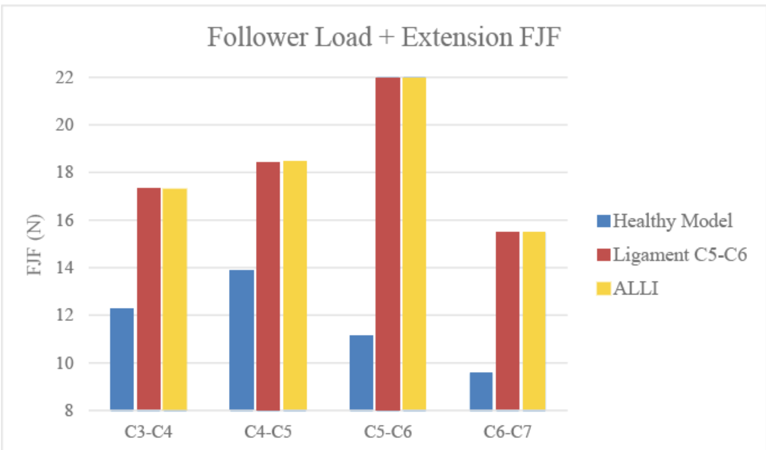

Figure 4. Results of the force between the facet joints in extension toque movement in traumatic injury and healthy models along with follower load

and 7.07% decrease in intradiscal pressure in conditions of ligament tear at the same level and adjacent ligament tear, respectively. Meanwhile, a 1.29% increase was observed at the C_4-C_5 level in the presence of ligament tear at the same level. On the other hand, intradiscal pressure was predicted to decrease by 1.4% in the presence of adjacent ligament tears. There were significant changes in the intradiscal pressure at the C_5-C_6 level due to the trauma of spondylolisthesis and displacement of the vertebra. The traumatic injury model with tear at the same level and tear of the adjacent ligaments reduced by 12.85% and 9.06%, respectively. On the other hand, 4.28% and 3.42% elevation was found in intradiscal pressure in the presence of ligament tear at the same level and the tear of the adjacent ligaments, respectively. However, things were different in the flexion and extension movements at the adjacent levels of the injury, compared to the other levels, which were mainly related to intradiscal pressure (Figure 3).

While pressure mostly augmented in the adjacent levels, the reduction in pressure was lower in these levels, compared to other levels. Increased pressure in the inner core of the vertebral disc might damage these levels in long term and result in intervertebral disc degeneration at the adjacent levels. There was a difference between the flexion and extension movements in the presence of ligament tear at the same level and the tear of adjacent ligaments, in comparison with other movements, in terms of intradiscal pressure results. This could be attributed to the posterior ligament tear and soft tissue damage at distinct levels.

The facet joint forces were estimated in line with the extension movement, and the results demonstrated an extreme augmentation in facet joint force with trauma modeling, which led to the spondylolisthesis and displacement of the vertebra at the C_5-C_6 level. In this regard, the facet joint force results were higher (97.63%) at the C_5-C_6 level, compared to other segments. The findings indicated no significant difference between the two traumatic injury models of the tear of adjacent ligaments and ligament tear at the same level regarding facet joint force (Figure 4).

Discussion

The present study aimed to develop a patient-specific FEM for patients for the biomechanical prediction of the cervical spine of patients following a traumatic injury. First, we generated a personalized parametric geometric model based on 16 anatomical parameters extracted from the radiographic images of the patient. One of the differences and advantages of the current research, compared to previous biomechanical investigations, was modeling according to radiography images from two posterior and AP angles. Compared to other accurate models, our model was able to update the anatomical parameters of each patient more rapidly and accurately [(20)]. In the current study, all anatomical dimensions were directly extracted from the radiographs of each individual, and the aforementioned software was used for the design and analysis of each section separately to increase the accuracy of modeling. Moreover, intervertebral rotation results caused by net torque application in each segment were separately compared to the intervertebral rotation results of the in vitro experiments of Panjabi and Wheeldon to evaluate and validate the customized parametric FEM [(18, 19)]. In addition, our model was compared with the previous biomechanical studies in terms of intervertebral rotation, facet joint force, and intradiscal pressure. The results of the comparison were numerically well-matched [(6, 21)]. In the current investigation, the traumatic injury models were designed and developed based on the previous clinical studies [(7, 11)]. Moreover, the biomechanical response of the cervical spine under diverse loads was evaluated regarding the parameters of intervertebral rotation, facet joint force, and intradiscal pressure. The results were shown to be numerically well-matched with previous biomechanical studies [(22)].

Given the significance of trauma to the cervical spine, the current research attempted to reduce the number of unnecessary MRIs, which could improve patient safety and decrease treatment costs. Furthermore, the present model could have proper clinical uses and could enable surgeons to predict surgical outcomes in the shortest possible time by updating the model based on the information of each patient pre-operation and using the results, such as intradiscal pressure, range of motion, and face force. Therefore, they could reduce associated complications, as well as the direct and indirect economic burden to the patient and community, medical issues, and concerns related to guaranteeing the quality and validity of selective criteria for possible damage to soft tissues and ligaments due to cervical spine injury, which is an important priority. One of the major limitations of the present study was modeling based on the anatomical data of the patient and FEM usage. In addition, the spine surgeon decided about the need for more imaging and a suitable surgical approach. Another limitation of the present study was the lack of accurate simulation of muscular forces, which affected the spine. It is recommended to add these details to the model to attain more accurate results, compared to real human models.

Conclusion

The current research presented a geometrical parametric model of the cervical spine using radiography images. The model was built in Hyper Mesh software and the ligaments were added to the model. Afterwards, the FEM developed in the study was transferred to ABAQUS software. The FEM analysis revealed a proper match with experimental data. Following the simulation of two types of traumatic injuries of vertebra displacement and spondylolisthesis with reduced disc height and facet joint dislocation at the C_5-C_6 segment, the results related to intervertebral rotation, intradiscal pressure, and facet joint force were calculated in the presence of adjacent ligament tears and the tear of ligaments at the same level. Moreover, the biomechanical behavior of the model was discussed and assessed at various levels. According to our results, trauma modeling caused some changes in the biomechanical behavior of the model, including a reduced range of motion in most levels in different movements, diminished intradiscal pressure in most levels, and higher facet joint force. This structural disruption in this complex system caused abnormal behavior in various movements. The findings of the current investigation demonstrated that the lack of improvement in the biomechanical behavior of the model would cause spinal instability and could increase the probability of injuries in distinct segments of the lower cervical spine in long term.

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