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Evaluation of the influence of atlantoaxial transverse ligament on stability of atlantoaxial complex fracture using 3D finite element method

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Abstract: Objective To analyze and compare the effects of transverse ligament injury on the stability and stress distribution of atlantoaxial complex fractures using 3D finite element method. **Methods** A male volunteer with a normal cervical spine was selected. The cranio-cervical region (C0-C3) was scanned using a 64-slice spiral CT scanner. Software such as Simpleware 3.0, Geomagic 12.0, and Hypermesh 12.0 were used to create a three-dimensional finite element model (FEM/Intact) of the C0-C3 segment. On the validated model, the anterior and posterior arches of C1 and the base of the odontoid process were fractured to create a composite fracture model (FEM/Fracture) simulating Jefferson/Type II odontoid fracture. Two additional models were created: one with a ruptured transverse ligament of the atlas (FEM/RTL) and another with an intact transverse ligament (FEM/TL). The models were subjected to loading conditions of flexion, extension, lateral bending, and rotation, and the Von Mises stress distribution and vertebral segment motion were analyzed for each model under different loading conditions. **Results** The three-dimensional nonlinear finite element model of the atlantoaxial complex created in this study had a realistic appearance and good geometric similarity. The motion of each vertebral segment in the model was consistent with the results of Panjabi's in vitro experimental analysis. The composite fracture model of Jefferson/Type II odontoid fracture with or without transverse ligament injury also had a realistic appearance and good geometric similarity. After combining the transverse ligament injury with the Jefferson/Type II odontoid fracture, the instability of the upper cervical spine primarily concentrated at the atlantoaxial joint, with varying degrees of increased motion in flexion, extension, lateral bending, and axial rotation compared to the normal group.**Conclusion** Transverse ligament injury significantly affects the stability and stress distribution of atlantoaxial complex fractures. The finite element models established in this study can be used for biomechanical analysis of Jefferson/Type II odontoid fracture combined with transverse ligament injury, and provide strong theoretical support for the selection of fixation methods in atlantoaxial complex fractures.

Keywords: Finite element; Atlas; axis; Fracture; Atlantoaxial transverse ligament; Fracture stability

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Background

The transverse ligament of atlas is a tough and thick ligament, which connects the medial surfaces of the lateral masses of atlas, with a slightly concave front and a slightly wide middle. The transverse ligament of atlas has an articular surface composed of fibrocartilage of atlas, which is related to odontoid process. Transverse ligament plays an important role in the stability of atlantoaxial axis, especially in preventing the atlas from moving forward and maintaining the normal position of the atlantoaxial space.[1]. The transverse ligament is mainly composed of collagen fibers, but less elastic fibers. The collagen fibers interweave with each other in the central part of the transverse ligament at an included angle of 30, so the transverse ligament has high stiffness and insufficient elasticity.[2] When the odontoid process of the axis is fractured, dislocation can be effectively prevented if the transverse ligament of the atlas remains intact.[3]. Simple transverse ligament injury of atlas is not common, while transverse ligament injury of atlas is common in atlantoaxial compound fracture.[4] Jefferson/type Ⅱ odontoid fracture is the most common in atlantoaxial complex fracture.[5] Jefferson/type Ⅱ odontoid fracture can lead to the loss of stability of atlantoaxial complex and abnormal movement of the motion segment between atlantoaxial and atlantoaxial.[6] After Jefferson/type Ⅱ odontoid fracture of cervical vertebra, it will not only lead to the loss of stability of atlantoaxial complex, but also lead to the injury or tear of transverse ligament of atlas, which may further aggravate the loss of stability of atlantoaxial complex.[7] However, the effects of the integrity of the transverse ligament of the atlas on the stability of the upper cervical spine have not been proved by research. Therefore, this study intends to use the three-dimensional finite element model of atlantoaxial complex established in the previous period.[8] Furthermore, a three-dimensional finite element model of Jefferson/type ⅱ odontoid fracture with or without atlantoaxial ligament injury was established, and the influence of atlantoaxial ligament injury on the stability of upper cervical spine was evaluated by finite element analysis.

1 Material and methods

1.1 Establishment of normal upper cervical vertebra model and Jefferson/Type Ⅱ odontoid fracture finite element model

A 27-year-old healthy male volunteer, weighing 64 kg and with a height of 174 cm, was selected. The participant had no history of cervical spine trauma or surgery, and underwent X-ray examination in the open-mouth position and in the anteroposterior, lateral, hyperextension, and hyperflexion positions of the cervical spine to exclude deformities and pathological changes. The participant had no history of chronic diseases or cervical spondylosis. After obtaining informed consent, a GE Lightspeed 64-slice spiral CT (General Electric Company, USA) was used to perform a scan of the volunteer's craniocervical region at a slice thickness of 0.625 mm. The CT data were imported into Simpleware 3.0 software (Simpleware Ltd, UK) in DICOM format and processed for segmentation, noise reduction, and filtering to create an STL triangular mesh model, which was then used in Geomagic 12.0 (Parametric Technology Corporation, USA) for surface simulation to generate a NURBS surface model. The resulting NURBS surface model was processed using Hypermesh 12.0 (Altair Engineering Inc., USA) for contact definition, meshing, material assignment, and boundary constraints. Contact definition: A 2-node nonlinear spring element was used to establish 12 types of ligaments (Transverse ligament of the atlas (TLA), Alar ligament (AL), Anterior atlanto-occipital membrane (AAOM), Anterior longitudinal ligament (ALL), Ligamentum flavum (LF), Posterior longitudinal ligament (PLL), Posterior atlanto-occipital membrane (PAOM), Capsular ligament (CL), Tectorial membrane (TM), Apical ligament of the Odontoid process of axis (AP), Supraspinal ligament (SSL), Interspinous ligament (ISL), totaling 12 ligaments); a nonlinear surface-to-surface general contact relationship was used to simulate the interaction between joints. Meshing: Cortical bone was meshed with an average thickness of 1 mm using C3D6 elements; trabecular bone was meshed with C3D4 elements; the endplate was meshed with 0.5 mm thick C3D6 elements; ligaments were meshed using 2-node SPRINGA spring elements with only axial translational freedom; the intervertebral disc was coupled; the skull was set as a rigid body structure, meshed with C3D8 elements. The mesh quality Jacobian ratio was controlled above 0.6. Material properties: Trabecular bone, cortical bone, and the transverse ligament were assigned with orthotropic material properties; the remaining ligaments were defined based on elastoplastic material properties; the intervertebral disc (including the nucleus pulposus and annulus fibrosus) was set as an incompressible hyperelastic material (based on the strain energy theory of the Mooney-Rivlin hyperelastic material formula, parameters: C10, C01) [9]. Ligament parameters were sourced from published references [10], and a normal C0-C3 segment three-dimensional finite element model (FEM/Intact) was established. [9][10] Then, on the basis of the established normal C0-C3 segment finite element model, the anterior and posterior arches of C1 were directly fractured, and the base of the Odontoid process of axis was cut to simulate a Jefferson/Type II odontoid fracture, establishing a complex fracture finite element model (FEM/Fracture). The Von Mises stress cloud map and the range of motion (ROM) of each vertebral segment under the conditions of the fracture and with the transverse ligament intact and the transverse ligament ruptured were analyzed, and compared with the normal model.

1.2 Establishment of a Finite Element Model for Jefferson/Type Ⅱ odontoid fracture combined atlantoaxial fracture with Transverse Ligament Rupture

Dickman [11] classified injuries to the transverse ligament of the atlas into two types: Type I involves the rupture of the transverse ligament itself, with Type Ia being a midsubstance tear of the ligament and Type Ib being an avulsion fracture at the ligament's attachment site; Type II involves an avulsion fracture at the ligament's attachment site with a bony component, with Type IIa being a comminuted fracture of the lateral mass of the atlas, and Type IIb being an avulsion fracture of the superior articular process of the atlas. Type II injuries of the transverse ligament are more complex, and rupture of the transverse ligament often presents a "whole or none" phenomenon, lacking the capacity for post-injury repair [2]. To facilitate the establishment of a finite element model, this study employed a method of removing the transverse ligament elements posterior to the Odontoid process of axis to simulate injuries of the transverse ligament type [12].

1.3 Model Validation and Experimental Loading

The finite element model is imported into the finite element analysis software Abaqus 6.9. All six degrees of freedom of the endplate under constraint C3 are taken as boundary conditions. Select a reference point on the axis of rotation of the upper cervical vertebra, and establish the Distribution Coupling of all unit nodes at this reference point (this constraint method can convert the stress on the reference point into uniform load and apply it to all slave nodes). Apply a pure torque of 1.5 nm to the reference point with global coordinates of X, Y and Z respectively (X-Y plane is horizontal, X-Z is coronal, and Y-Z is sagittal), and apply a preload of 50 N and a torque of 1.5 N m to the occipital bone, so that it can generate flexion, extension, rotation and lateral flexion. Using Abaqus6.9 software, all units of the model under different working conditions are displayed in the form of cloud images.

Different colors represent different stress sizes, and the size of color areas represents the size of stress distribution areas, which can show the stress concentration areas of the model under different loads and working conditions. The stress nephogram of ROM and Von Mises of each vertebral segment (C0-C1, C1-C2, C2-C3) under the condition of fracture and fracture of transverse ligament of atlas were analyzed, and compared with the normal model.

2 Results

2.1 C0-C3 finite element model and Jefferson/Type Ⅱ odontoid fracture combined atlantoaxial fracture finite element model

The normal C0-C3 finite element model established in this experiment is visually realistic and has good geometric similarity. It comprises a total of 211,371 elements and 66,517 nodes (**see Figure 1**). The range of motion of each vertebral segment in the model is essentially in agreement with the analytical results published by Panjabi [13-14] (**see Figure 2**). The reliability and validity of the model have been verified. Subsequently, on the basis of this model, the anterior and posterior arches of C1 can be directly fractured along with the transverse ligament severed at the base of the Odontoid process of axis, to simulate a Jefferson/Type II odontoid fracture, thereby establishing a finite element model for Jefferson/Type II odontoid fracture of the atlantoaxial complex.

2.2 Jefferson/II odontoid fracture model of atlantoaxial complex fracture with intact and broken transverse ligament, and the mobility of each vertebral segment

Based on the normal C0-C3 finite element model, a finite element model for Jefferson/Type II odontoid fracture with transverse ligament injury was established. The comparison of the range of motion (ROM) at the C0-C1, C1-C2, and C2-C3 segments under different conditions between the intact and the transverse ligament injury models is shown in Figure 3. It can be observed that the presence or absence of transverse ligament injury has no significant effect on the ROM of the C0-C1 segment during flexion, extension, and lateral bending. However, the model with combined transverse ligament injury exhibited an increased torsion of 3.5°, which is a 35.2% increase. The presence or absence of transverse ligament injury affects the ROM of the C1-C2 segment

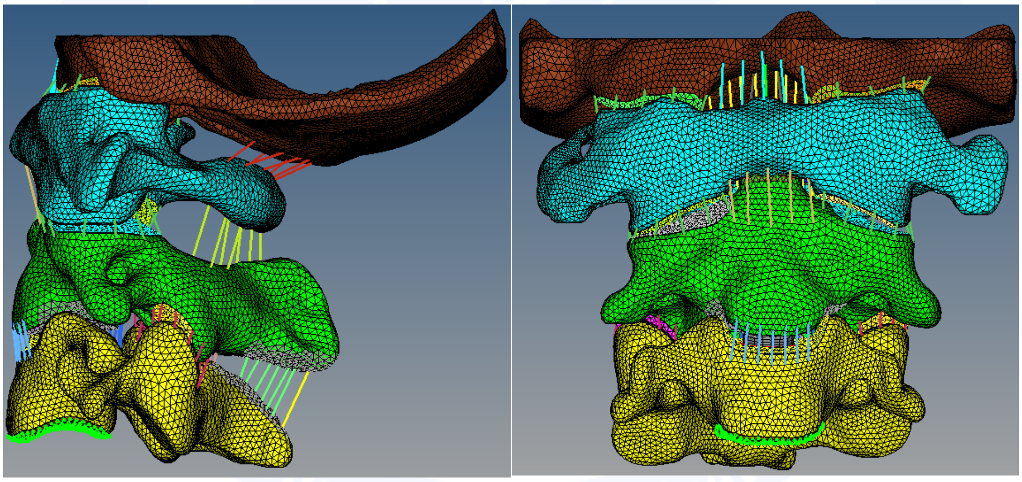

Fig. 1 Normal C0-C3 Finite Element Model

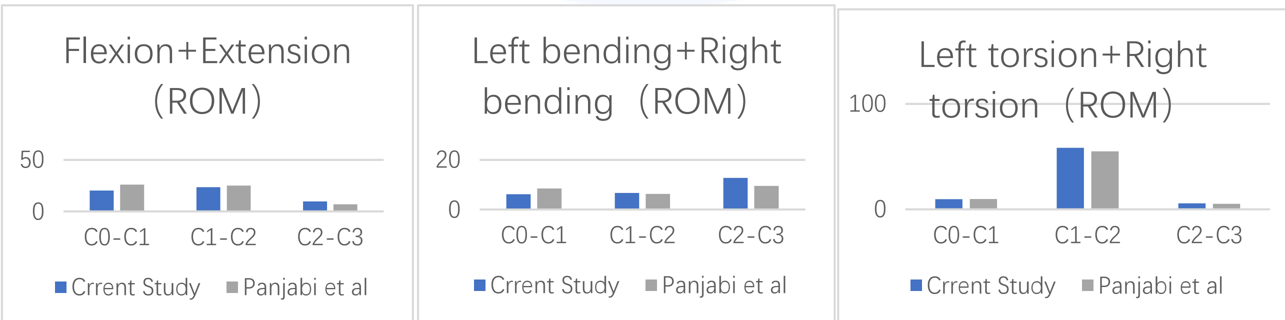

Fig. 2 Activity of each vertebral segment in the finite element model of the atlas axis complex

under various conditions. The model with combined transverse ligament injury showed an increased ROM of

12.3° in flexion combined with extension, 0.3° in lateral bending (left and right), and 5.5° in rotation, representing increases of 34.9%, 3.9%, and 7%, respectively. After complex fractures of the atlantoaxial joint, instability of the upper cervical spine, particularly at the atlantoaxial joint, is caused by injuries to the transverse ligament. During flexion and extension movements, there is a significant increase in joint ROM, and the stability of the upper cervical spine is also markedly reduced [15]. It can be seen from the figure that after injury to the transverse ligament, there is a noticeable increase in the ROM of the C1-C2 segment. This further confirms that if a Jefferson/Type II odontoid fracture is combined with an injury to the transverse ligament, it will have a significant impact on the stability of the atlantoaxial joint, especially during flexion and extension [16].

2.3 Comparison of Stress Distribution in Upper Cervical Spine Models with Transverse Ligament Injury Combined with Jefferson/Type II odontoid fracture versus Models without Transverse Ligament Injury

A preload of 50 N and a torque of 1.5 N·m were applied to the occipital bone, and the stress distribution under various motions was compared between the Jefferson/Type II odontoid fracture model with transverse ligament injury of the atlas and the model without transverse ligament injury (see Figure 4). In the model with transverse ligament injury, the maximum stress during flexion and extension appeared in the region of the superior articular surface of C1 and C2, which increased by 0.86 MPa and 1.78 MPa, respectively, compared to the intact model. This is because, after injury to the transverse ligament of the atlas, the restraining effect of the transverse ligament on the Odontoid process of axis is lost, leading to a decrease in the force acting on the anterior arch of the atlas and an increase in the interaction of the atlanto-occipital joint, thereby increasing the maximum stress [17]. During lateral bending and axial rotation, the impact of transverse ligament injury on the stress distribution of the upper cervical spine model was minimal because the primary function of the transverse ligament is to prevent anterior dislocation of the atlas [18]. Additionally, after a Jefferson/Type II odontoid fracture has occurred, the ability of the atlantoaxial joint to maintain rotation is essentially lost; therefore, the presence or absence of injury to the transverse ligament has little impact on the instability of the upper cervical spine during lateral bending and axial rotation in the context of a Jefferson/Type II odontoid fracture.

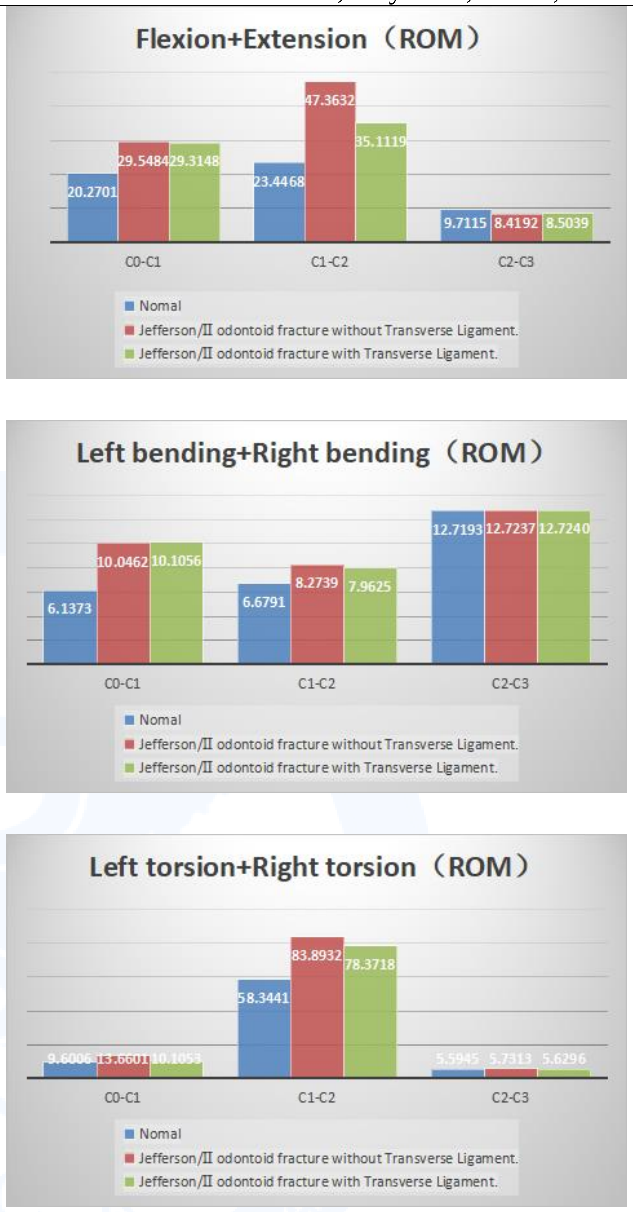

Fig. 3 Comparison of joint mobility between transverse ligament injury model and non-destructive model

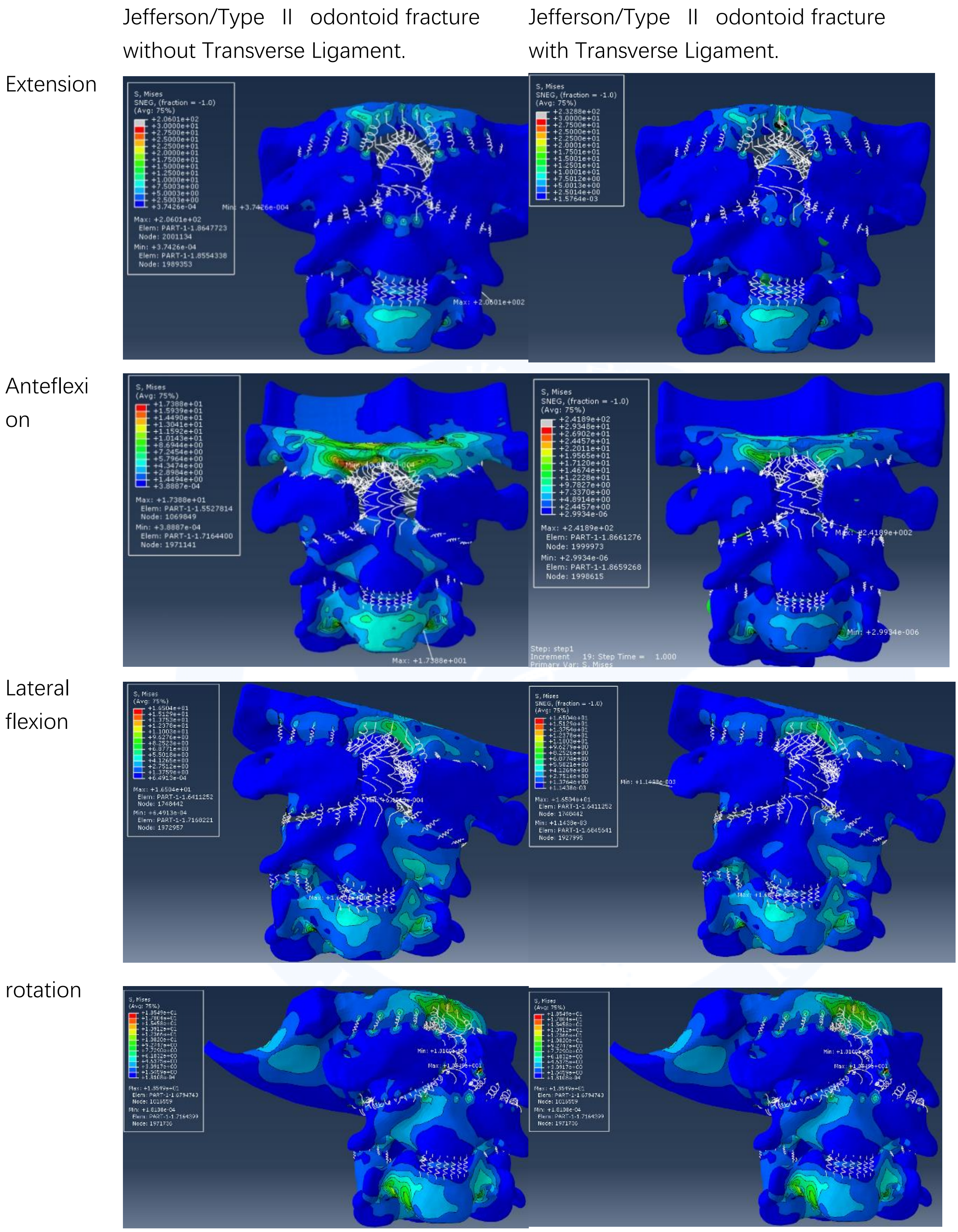

Fig. 4 Comparison of stress distribution between intact and fractured transverse ligaments in composite fractures of the atlas axis

3 Discussion

3.1 Anatomical characteristics of the transverse ligament of the atlas

The transverse ligament of the atlas attaches laterally to the tubercles on both sides of the lateral masses of the atlas and medially to the posterior part of the Odontoid process of axis of the axis, forming the atlantoaxial joint together with the anterior arch of the atlas, the lateral masses, and the Odontoid process of axis of the axis. The stability between the atlas and axis is primarily maintained by intact ligamentous structures [19]. The transverse ligament plays a role in maintaining joint stability and limiting excessive joint motion. It divides the spinal canal of the atlas into an anterior and a posterior part, with the anterior part accommodating the Odontoid process of axis and the posterior part housing the spinal cord and its membranes. Additionally, it also serves to limit posterior displacement of the odontoid process of axis [19]. Injury to the transverse ligament can lead to instability between the atlas and axis, potentially resulting in anterior dislocation of the atlas, which can severely injure the medulla oblongata, leading to high-level quadriplegia or even death in patients [20]. The stability of an atlantoaxial complex fracture mainly depends on the condition of the transverse ligament and the alar ligaments. The transverse ligament is crucial for fixing the Odontoid process of axis, stabilizing the atlantoaxial joint, and maintaining tension between the bilateral lateral masses of the atlas. If the transverse ligament is not damaged, the separation and displacement of the two lateral masses will be limited, and the total lateral displacement of both sides must be less than 6.9 mm. However, if the transverse ligament is completely ruptured, the two lateral masses will lose ligamentous control, leading to centrifugal separation and displacement greater than 6.9 mm, thereby exacerbating instability in the region [21].

3.2 The Anatomical Characteristics of Jefferson/Type II odontoid fracture and the Impact of the Presence or Absence of the Transverse Ligament on Its Stability

Jefferson/Type II odontoid fracture of the Atlantoaxial Complex is a special type of atlantoaxial complex fracture, accounting for approximately 12% of Odontoid process of axis fractures [22]. It is characterized by a fracture line that involves the junction between the Odontoid process of axis and the body of the axis. This type of fracture is usually caused by sudden axial vertical force applied to the atlas while a flexion force is applied to the axis Odontoid process of axis [23]. Jefferson/Type II odontoid fracture can lead to the loss of stability of the atlantoaxial complex, resulting in abnormal motion between the atlas and axis [24]. After the occurrence of Jefferson/Type II odontoid fracture, the cervical spine not only loses stability of the atlantoaxial complex and exhibits abnormal motion between the atlas and axis, but it may also lead to injury or rupture of the transverse ligament, further exacerbating the loss of stability of the atlantoaxial complex [25]. This study constructed a finite element model of Jefferson/Type II odontoid fracture combined with transverse ligament injury of the atlas and performed comparative analysis on the range of joint motion and stress distribution. The results showed that after injury to the transverse ligament, the range of motion of the atlantoaxial joint increased under various activities. The simulation results further confirmed that injury to the transverse ligament would significantly alter the range of motion of the atlantoaxial joint, which is consistent with the conclusion that the atlas is prone to anterior dislocation after injury to the transverse ligament [3, 18, 12].

3.3 Problems in finite element analysis of Jefferson/ Type II odontoid fracture complicated with transverse ligament injury

The finite element model established in this study aims to delve into the biomechanical characteristics of Jefferson/Type II odontoid fracture combined with transverse ligament injury of the atlas. The application of this model extends beyond the analysis of fractures and transverse ligament injuries; it also provides robust theoretical support for the selection of fixation methods for upper cervical spine injuries in atlantoaxial complex fractures. However, the model does have certain limitations. The atlantoaxial complex, as a complex structure, has biomechanical properties that are not solely dependent on bones and ligaments but are also significantly influenced by muscles and soft tissues. Due to technical constraints, the model in this study did not fully incorporate these factors, which may result in discrepancies between the simulated range of motion (ROM), stress distribution, and actual conditions. Furthermore, this experiment only simulated Jefferson/Type II odontoid fractures, whereas the fracture patterns of the atlantoaxial complex may be more intricate. Additional research and simulation are required for other types of atlantoaxial complex fractures combined with transverse ligament injuries to more comprehensively elucidate the biomechanical properties of the atlantoaxial complex and the transverse ligament. Additionally, the model developed in this study is a normal three-dimensional nonlinear finite element model of the upper cervical spine, without consideration for individual variations such as cervical spine degeneration and osteoporosis. Nevertheless, this model still provides a valuable research foundation and direction for future studies.

The authors report no conflict of interest

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·论　著·

应用三维有限元方法评价寰椎横韧带对寰枢椎复合骨折稳定性的影响

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摘要：目的　应用三维有限元方法分析并比较横韧带损伤与否对寰枢椎复合骨折稳定的影响与应力传导情况。**方法**　选择 1 名正常男性志愿者，采用 64 排螺旋 CT 机扫描枕颈部（C0～C3），利用 Simpleware 3.0、Geomagic 12.0、Hypermesh 12.0 等软件建立 C0～C3 节段三维有限元模型（FEM/Intact），并进行对比验证。在验证的模型基础上断裂 C1 前弓和后弓及切断齿状突基底部，模拟 Jefferson/Ⅱ型齿状突骨折的复合骨折有限元模型（FEM/Fracture）。在此基础上分别建立两种模型：寰椎横韧带断裂模型（FEM/RTL）及寰椎横韧带无损模型（FEM/TL）。对三种模型加载前屈、后伸、侧屈、旋转工况，分析各模型在不同工况下 Von Mises 应力云图及各椎节活动度。**结果**　本实验建立的寰枢椎复合体三维非线性有限元模型外观逼真，几何相似性好。模型各椎节的活动度与 Panjabi 发表的体外实验分析结果基本相吻合。而后建立的 Jefferson/Ⅱ型齿状突骨折的复合骨折模型及其合并寰椎横韧带损伤和完整的模型外观逼真，几何相似性好。Jefferson/Ⅱ型齿状突骨折的复合骨折合并寰椎横韧带损伤后上颈椎的不稳主要集中在寰枢关节，在前屈、后伸、侧弯和轴向旋转等工况下的关节活动度均比正常组有不同程度的增大。**结论**　寰椎横韧带损伤对寰枢椎复合骨折的稳定性与应力传导有明显影响。本文建立的有限元模型可以用于 Jefferson/Ⅱ型齿状突骨折合并横韧带损伤的生物力学分析，还可为寰枢椎复合骨折上颈椎固定方式的选择提供有力的理论支持。

关键词：有限元；寰椎；枢椎；骨折；寰椎横韧带；骨折稳定性

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Abstract: Objective　To analyze and compare the effects of transverse ligament injury on the stability and stress distribution of atlantoaxial complex fractures using 3D finite element method. **Methods**　A male volunteer with a normal cervical spine was selected. The cranio-cervical region (C0-C3) was scanned using a 64-slice spiral CT scanner. Software such as Simpleware 3.0, Geomagic 12.0, and Hypermesh 12.0 were used to create a three-dimensional finite element model (FEM/Intact) of the C0-C3 segment. On the validated model, the anterior and posterior arches of C1 and the base of the odontoid process were fractured to create a composite fracture model (FEM/Fracture) simulating Jefferson/Type Ⅱ odontoid fracture. Two additional models were created: one with a ruptured transverse ligament of the atlas (FEM/RTL) and another with an intact transverse ligament (FEM/TL). The models were subjected to loading conditions of flexion, extension, lateral bending, and rotation, and the Von Mises stress distribution and vertebral segment motion were analyzed for each model under different loading conditions. **Results**　The three-dimensional nonlinear finite element model of the atlantoaxial complex created in this study had a realistic appearance and good geometric similarity. The motion of each vertebral segment in the model was consistent with the results of Panjabi's in

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vitro experimental analysis. The composite fracture model of Jefferson/Type Ⅱ odontoid fracture with or without transverse ligament injury also had a realistic appearance and good geometric similarity. After combining the transverse ligament injury with the Jefferson/Type Ⅱ odontoid fracture, the instability of the upper cervical spine primarily concentrated at the atlantoaxial joint, with varying degrees of increased motion in flexion, extension, lateral bending, and axial rotation compared to the normal group. **Conclusion** Transverse ligament injury significantly affects the stability and stress distribution of atlantoaxial complex fractures. The finite element models established in this study can be used for biomechanical analysis of Jefferson/Type Ⅱ odontoid fracture combined with transverse ligament injury, and provide strong theoretical support for the selection of fixation methods in atlantoaxial complex fractures.

Keywords: Finite element; Atlas; Axis; Fracture; Atlantoaxial transverse ligament; Fracture stability

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寰椎横韧带是一根坚韧且肥厚的韧带,它连接了寰椎两侧侧块的内侧面,前面微凹,中部略宽。寰椎横韧带具有一个由寰椎纤维软骨构成的关节面,这一关节面与齿突相关节。横韧带在寰枢椎的稳定性上起到了主要作用,特别是在防止寰椎前移和维持寰齿间隙的正常位置方面[1]。横韧带主要由胶原纤维组成,而弹力纤维较少,胶原纤维在横韧带的中央部以30°夹角相互交织成网,因此横韧带刚度较高而弹性不足[2]。当枢椎齿突发生骨折时,如果寰椎横韧带保持完整,可以有效地防止脱位[3]。单纯寰椎横韧带损伤不常见,寰椎横韧带损伤常见于寰枢椎复合骨折[4],寰枢椎复合骨折中,又以 Jefferson/Ⅱ型齿状突骨折最为常见[5],Jefferson/Ⅱ型齿状突骨折可以导致寰枢椎复合体的稳定性丧失,使寰椎和枢椎之间的运动节段发生异常活动[6]。颈椎在发生 Jefferson/Ⅱ型齿状突骨折后,除了会导致寰枢椎复合体的稳定性丧失,使寰椎和枢椎之间的运动节段发生异常活动外,同时还可能导致寰椎横韧带损伤或撕裂,进而可能进一步加重寰枢椎复合体的稳定性丧失[7]。但是寰枢椎复合骨折后寰椎横韧带的完整与否对上颈椎的稳定性有哪些影响尚未有研究证明。因此,本研究拟利用前期建立的寰枢椎复合体三维有限元模型[8],进一步建立 Jefferson/Ⅱ型齿状突骨折的寰枢椎复合骨折合并有无寰椎横韧带损伤的三维有限元模型,利用有限元分析方法评价寰椎横韧带损伤在 Jefferson/Ⅱ型齿状突骨折的寰枢椎复合骨折中对上颈椎稳定性的影响。

1　资料和方法

1.1　正常上颈椎模型和 Jefferson/Ⅱ型齿状突骨折有限元模型的建立　选取 1 名 27 岁健康男性志愿者,体质量 64 kg,身高 174 cm,无颈椎外伤和手术史,行张口位及颈椎正侧位、过伸过屈位 X 射线检查,排除畸形及病变;既往无慢性疾病,无颈椎病史。获得其知情同意后,采用 GE Lightspeed 64 排螺旋 CT(美国 GE 公司)按 0.625 mm 对其枕颈部进行扫描。将 CT 数据以 Dicom 格式导入 Simpleware 3.0 软件(英国 Simple-ware 公司)进行分割降噪滤波处理,转化为 STL 三角网格模型,再利用 Geomagic 12.0(美国 PTC 公司)进行曲面模拟生成非均匀有理 B 样条(NURB)曲面模型。

将得到的 NURB 曲面模型经 Hypermesh 12.0(美国 Altair 公司)进行接触定义、网格划分、材料赋值、边界约束等。接触定义:采用 2 节点非线性弹簧单元建立 12 种韧带[寰椎横韧带(TLA)、翼状韧带(AL)、寰枕前膜(AAOM)、前纵韧带(ALL)、黄韧带(LF)、后纵韧带(PLL)、寰枕后膜(PAOM)、关节囊韧带(CL)、覆膜(TM)、齿突尖韧带(AP)、棘上韧带(SSL)、棘间韧带(ISL)];采用非线性面面通用接触关系模拟关节间的相互作用。网格划分:皮质骨采用平均厚度为 1 mm 的C3D6 单元;松质骨采用 C3D4 单元;终板采用 0.5 mm 厚的 C3D6 单元;韧带采用只有轴向平移自由度的、双节点 SPRINGA 弹簧单元进行划分;椎间盘采用 coupling 连接;颅骨设为刚体结构,采用 C3D8 单元。网格质量 Jacobian 比控制在 0.6 以上。材料属性:松质骨、皮质骨、横韧带采用正交各向异性材料赋值;其余韧带基于弹塑性材料属性进行定义;椎间盘(含髓核与纤维环)设定为不可压缩的超弹材料(基于应变能理论的 Mooney-Rivilin 超弹材料公式,参数:C10,C01)[9]。韧带参数来源于已发表的参考文献[10],建立正常 C0~C3 节段三维有限元模型(FEM/Intact)。

然后在已建立的正常 C0~C3 节段有限元模型的基础上,直接断裂 C1 前弓和后弓+切断齿状突基底部,模拟 Jefferson/Ⅱ型齿状突骨折,建立复合骨折有限元模型(FEM/Fracture)。分析骨折状态下寰椎横

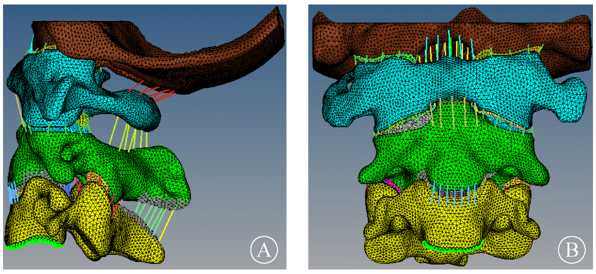
韧带完整和寰椎横韧带断裂的情况下 Von Mises 应力云图以及各椎节活动度(range of motion, ROM),同时与正常模型对比。

1.2　横韧带断裂的 Jefferson/Ⅱ型齿状突骨折有限元模型的建立　Dickman 等[11]将寰椎横韧带损伤分为:Ⅰ型横韧带本身断裂,Ⅰa 型为韧带中部的断裂,Ⅰb 型为韧带附着部的断裂;Ⅱ型韧带附着部骨性的断裂,Ⅱa 型为寰椎侧块的粉碎性骨折,Ⅱb 型为寰椎侧块内结节撕脱骨折。Ⅱ型横韧带损伤较为复杂,寰椎横韧带断裂常表现为一种“全或无”的现象,损伤后无修复能力[2],为方便有限元模型的建立,本文采用去除齿状突后方横韧带单元结构的方法模拟横韧带型损伤[12]。

1.3　模型的验证与实验加载　将有限元模型导入有限元分析软件 Abaqus 6.9 中。约束 C3 下终板全部 6 个自由度作为边界条件。在上颈椎旋转轴上选择一参考点,建立此参考点所有单元节点的 Distribution Coupling(该约束方式可以将参考点上的受力情况换算成均布载荷施加于所有从节点上)。对参考点施加大小为 1.5 N · m,方向分别为 X、Y、Z 全局坐标的纯扭矩(X-Y 平面为水平面、X-Z 为冠状面、Y-Z 为矢状面),在枕骨上施加 50 N 的预载荷和 1.5 N · m 的扭矩,使其产生前屈、后伸、旋转、侧屈运动。运用 Abaqus 6.9 软件,将不同工况下模型各个单位以云图形式显示出来,不同颜色代表不同的应力大小,色区的大小代表应力分布区域的大小,可以显示出模型在不同载荷不同工况下的应力集中区域。分析骨折状态下寰椎横韧带完整和寰椎横韧带断裂的情况下各椎节(C0~C1、C1~C2、C2~C3)关节活动度(ROM)以及 Von Mises 应力云图,同时与正常模型对比。

2　结　果

2.1　C0~C3 有限元模型及 Jefferson/Ⅱ型齿状突骨折的寰枢椎复合骨折的有限元模型　本实验建立的正常 C0~C3 有限元模型外观逼真,几何相似性好。共包含 211 371 单元,66 517 个节点(图 1)。模型各椎节的活动度与 Panjabi 等[13-14]发表的分析结果基本相吻合(图 2)。模型的可靠性和有效性得到了验证。进而可以在此基础上直接断裂 C1 前弓和后弓+切断齿状突基底部,模拟 Jefferson/Ⅱ型齿状突骨折,建立 Jefferson/Ⅱ型齿状突骨折的寰枢椎复合骨折的有限元模型。



注:A 为侧位视图;B 为正位视图。

图 1　正常 C0~C3 有限元模型

Fig. 1　Normal C0~C3 finite element model

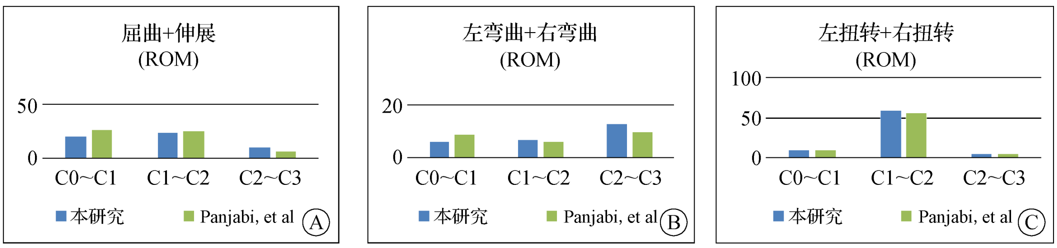


图 2　寰枢椎复合体有限元模型各椎节 ROM

Fig. 2　Activity of each vertebral segment in the finite element model of the atlas axis complex

2.2　Jefferson/Ⅱ型齿状突骨折的寰枢椎复合骨折模型合并横韧带完整和断裂的各椎节活动度　在正常 C0~C3 有限元模型的基础上建立 Jefferson/Ⅱ型齿状突骨折的有限元模型横韧带损伤模型与无损模型在不同工况下 C0~C1、C1~C2 和 C2~C3 节段的椎节 ROM 对比结果如图 3 所示。可见,有无横韧带损伤对 C0~C1 节段在前屈、后伸、侧弯时无明显影响,但合并横韧带损伤的扭转增大了 3.5°,增大了 35.2%。有无横韧带损伤对 C1~C2 节段在各种工况下的椎节 ROM 均有影响,合并横韧带损伤的模型在前屈+后伸、侧弯(左+右)和旋转的工况下 ROM 分别增大了 12.3°、0.3°和 5.5°,分别增大了 34.9%、3.9%、7.0%。寰枢椎复合骨折后,由于寰椎横韧带损伤导致上颈椎不稳,特别是在寰枢关节。在屈伸动作中,ROM 明显

增加，上颈椎的稳定性也显著降低[15]。从图中可以看出，横韧带损伤后，C1～C2 节段的 ROM 明显增加。这进一步证明，如果 Jefferson/Ⅱ型齿状突骨折合并横韧带损伤，会对寰枢关节的稳定性产生重大影响，特别是在前屈和后伸的时候[16]。

2.3　Jefferson/Ⅱ型齿状突骨折的合并横韧带损伤上颈椎模型与无横韧带损伤模型应力分布情况的对比　在枕骨上施加 50 N 的预载荷和 1.5 N·m 的扭矩，对比了寰椎横韧带损伤的 Jefferson/Ⅱ型齿状突骨折模型与寰椎横韧带无损模型在各种动作下的应力分布情况（图 4）。在寰椎横韧带损伤模型中，前屈和后伸时，最大应力出现在 C1 和 C2 的上关节面区域，且比无损模型分别增加了 0.86 MPa 和 1.78 MPa。这是因为寰椎横韧带损伤后，寰椎横韧带对齿状突原有的约束作用消失，导致寰椎前弓的受力作用减小，

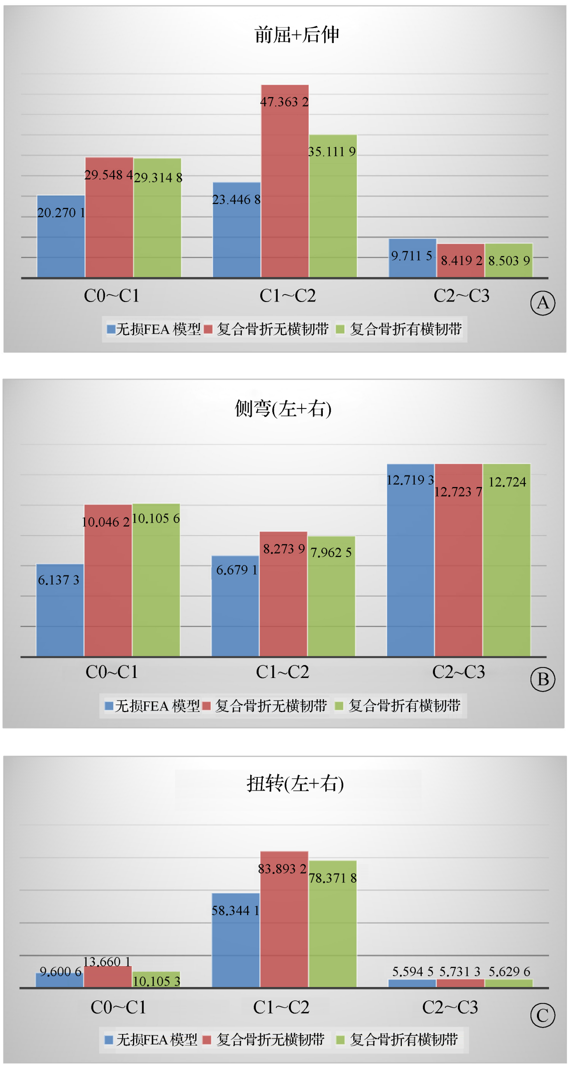


图 3　横韧带损伤模型与无损模型关节活动度对比

Fig. 3　Comparison of joint mobility between transverse ligament injury model and non-destructive model

而寰枕关节的相互作用变大，从而使得最大应力变大[17]。在侧弯和轴向旋转时，寰椎横韧带损伤对上颈椎模型的应力分布影响较小，因为寰椎横韧带主要的作用是防止寰椎发生前脱位[18]，同时，在已发生 Jefferson/Ⅱ型齿状突骨折后，寰枢关节维持旋转的功能基本是丧失的，因此，有无寰椎横韧带的损伤对 Jefferson/Ⅱ型齿状突骨折后的上颈椎在侧弯和轴向旋转时的不稳影响不大。

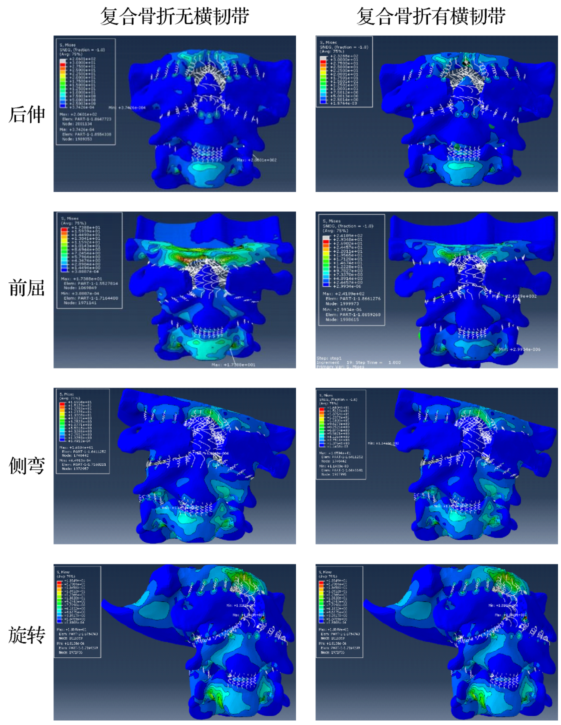


图 4　寰枢椎复合骨折横韧带完整与横韧带断裂的应力分布情况的对比

Fig. 4　Comparison of stress distribution between intact and fractured transverse ligaments in composite fractures of the atlas axis

3　讨　论

3.1　寰椎横韧带的解剖特点　寰椎横韧带两侧止于寰椎双侧侧块的骨突上，中间附着于枢椎齿突后部，寰椎前弓、侧块、横韧带和枢椎齿状突一起，构成了寰齿关节。寰枢椎之间的稳定性主要靠完整的韧带结构来维持[19]。寰椎横韧带的作用是维持关节稳定性和限制关节过度运动。它能够将寰椎的椎孔分为前、后两部，前部容纳齿突，后部容纳脊髓及其被膜。此外，它还能有限制齿突后移的作用[19]。一旦寰椎横韧带损伤，引发寰椎与枢椎间的不稳定，继而发生寰椎前脱位，严重者伤及延髓，导致患者高位四肢瘫痪甚至死亡[20]。寰枢椎复合骨折的稳定性主要取决于横韧带和翼状韧带的损伤状况。横韧带对固定齿突、

稳定寰枢关节以及保持寰椎两侧块间的张力起着至关重要的作用。如果横韧带没有受损,两侧块的分离移位将是有限的,其两侧移位的总和必然小于6.9 mm。然而,如果横韧带完全断裂,两侧块将失去韧带的控制,导致离心性分离移位大于6.9 mm,从而造成该区域的不稳定进一步加重[21]。

3.2 *Jefferson/Ⅱ型齿状突骨折的解剖特点以及有无寰椎横韧带对其稳定性的影响* Jefferson/Ⅱ型齿状突骨折的寰枢椎复合骨折是一种特殊的寰枢椎复合骨折,约占齿状突骨折的12%[22],其特点是骨折线涉及齿状突与枢椎体的连接部位。这种骨折通常是由于突然的轴向垂直暴力作用于寰椎的同时伴随屈曲暴力作用于枢椎齿状突导致[23]。Jefferson/Ⅱ型齿状突骨折可以导致寰枢椎复合体的稳定性丧失,使寰椎和枢椎之间的运动节段发生异常活动[24]。颈椎在发生Jefferson/Ⅱ型齿状突骨折后,除了会导致寰枢椎复合体的稳定性丧失,使寰椎和枢椎之间的运动节段发生异常活动;同时还可能导致横韧带损伤或撕裂,进而进一步加重寰枢椎复合体的稳定性丧失[25]。本研究构建了Jefferson/Ⅱ型齿状突骨折合并寰椎横韧带损伤的有限元模型,并对关节活动度和应力分布进行了比较分析。结果表明,寰椎横韧带损伤后,寰枢关节在各种活动下的关节活动度都有所增加。模拟结果进一步证实,寰椎横韧带损伤会导致寰枢关节的活动范围发生显著变化,这与横韧带损伤后寰椎易发生前脱位的结论相一致[3,12,18]。

3.3 *Jefferson/Ⅱ型齿状突骨折合并横韧带损伤有限元分析中存在的问题* 本文所建立的有限元模型,旨在深入探讨Jefferson/Ⅱ型齿状突骨折合并寰椎横韧带损伤的生物力学特性。这一模型的应用不仅限于对骨折和寰椎横韧带损伤的分析,还可为寰枢椎复合骨折上颈椎固定方式的选择提供有力的理论支持。当然,该模型也存在一定的局限性。寰枢椎复合体作为一个复杂的结构,其生物力学特性不仅仅取决于骨骼和韧带,肌肉、软组织等也起着重要的作用。由于技术的限制,本研究的模型未能完全包括这些因素,因此在模拟的椎节ROM、应力分布等方面可能与实际情况存在一定差异。此外,本实验仅针对Jefferson/Ⅱ型齿状突骨折进行了模拟,而寰枢椎复合体的骨折情况可能更为复杂,其他类型的寰枢椎复合骨折合并寰椎横韧带损伤的情况需要进一步的研究和模拟,以更全面地揭示寰枢椎复合体和寰椎横韧带的生物力学特性。还有,本研究建立的模型是正常上颈椎三维非线性有限元模型,颈椎退变、骨质疏松等个体差异并未考虑进去。尽管如此,本模型仍提供了宝贵的研究基础,为未来的研究提供了方向。

利益冲突 无

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