MECHANICAL BEHAVIOR OF THORACOLUMBAR CORONAL SPLIT FRACTURES: FINITE ELEMENT ANALYSIS

COMPORTAMENTO MECÂNICO DAS FRATURAS TORACOLOMBARES DO TIPO SPLIT CORONAL: ESTUDO POR ELEMENTOS FINITOS

COMPORTAMIENTO MECÁNICO DE LAS FRACTURAS TORACOLUMBARES DEL TIPO SPLIT CORONAL: ESTUDIO POR ELEMENTOS FINITOS

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ABSTRACT

Objective: To analyze the behavior of thoracolumbar fractures of the coronal split type using the finite element method. Methods: Two comparative studies were conducted through simulation of coronal split fractures in a finite model in which the first lumbar vertebra (L1) was considered to be fractured. In the first case, the fracture line was considered to have occurred in the middle of the vertebral body (50%), while in the second model, the fracture line occurred in the anterior quarter of the vertebral body (25%). The maximum von Mises stress values were compared, as well as the axial displacement between fragments of the fractured vertebra. Results: The stress levels found for the fracture located at half of the vertebral body were 43% higher (264.88 MPa x 151.16 MPa) than those for the fracture located at the anterior 25% of the vertebra, and the axial displacement of the 50% fractured body was also greater (1.19 mm x 1.10 mm). Conclusions: Coronal split fractures located in the anterior quarter of the vertebral body incurred less stress and displacements and are more amenable to conservative treatment than 50% fractures occurring in the middle of the vertebral body. ***Level of Evidence III; Experimental study.***

Keywords: Spine; Spinal Fractures; Tensile Strength.

RESUMO

Objetivo: Analisar o comportamento das fraturas toracolombares do tipo split coronal através de elementos finitos. Métodos: Foram realizados dois estudos comparativos através da simulação de fratura do tipo split coronal, em modelo finito, considerando que a primeira vértebra lombar (L1) estava fraturada. No primeiro caso, considerou-se que o traço da fratura ocorria na metade do corpo vertebral (50%), já no segundo modelo, o traço de fratura ocorria na porção anterior do corpo (25%). Foram comparados os valores de tensão máxima segundo von Mises, assim como o deslocamento axial sofrido entre os fragmentos da vértebra fraturada. Resultados: Na fratura localizada ao nível da metade do corpo vertebral, os níveis de tensões encontrados foram 43% maiores (264,88 MPa x 151,16 MPa) do que aqueles na fratura a 25% no terço anterior do corpo vertebral, em que o deslocamento axial da porção fraturada também foi mais elevado (1,19 mm x 1,10 mm). Conclusões: As fraturas do tipo split coronal localizadas no quarto anterior do corpo vertebral concentram menos tensões e deslocamentos, sendo mais passíveis de tratamento conservador em comparação às fraturas que ocorrem na metade do corpo vertebral. ***Nível de Evidência III; Estudo experimental.***

Descritores: *Coluna Vertebral; Fraturas da Coluna Vertebral; Resistência à Tração.*

RESUMEN

Objetivo: Analizar el comportamiento de las fracturas toracolumbares del tipo split coronal a través de elementos finitos. Métodos: Se realizaron dos estudios comparativos a través de la simulación de fractura del tipo split coronal, en modelo finito, considerando que la primera vértebra lumbar (L1) estaba fracturada. En el primer caso, se consideró que el trazo de la fractura ocurría en la mitad del cuerpo vertebral (50%), ya en el segundo modelo, el trazo de la fractura ocurría en la porción anterior del cuerpo (25%). Fueron comparados los valores de tensión máxima según von Mises, así como el desplazamiento axial sufrido entre los fragmentos de la vértebra fracturada. Resultados: En la fractura localizada al nivel de la mitad del cuerpo vertebral, los niveles de tensiones encontrados fueron 43% mayores (264,88 MPa x 151,16 MPa) que aquellos en la fractura a 25% en el tercio anterior del cuerpo vertebral, en que el desplazamiento axial de la porción fracturada fue también más elevado (1,19 mm x 1,10 mm). Conclusiones: Las fracturas del tipo split coronal localizadas en el cuarto anterior del cuerpo vertebral concentran menores tensiones y desplazamientos, siendo más susceptibles de tratamiento conservador en comparación a las fracturas que ocurren en la mitad del cuerpo vertebral. ***Nivel de Evidencia III; Estudio experimental.***

Descriptores: *Columna Vertebral; Fracturas de la Columna Vertebral; Resistencia a la Tracción.*

Study conducted at the Hospital São Vicente de Paulo (HSVP)/Instituto de Ortopedia e Traumatologia de Passo Fundo (IOT) and the Bioengineering, Biomechanics, and Biomaterials Laboratory of the Universidade de Passo Fundo (UPF), Passo Fundo, RS, Brazil.
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INTRODUCTION

Coronal split fractures in the thoracolumbar spine can occur through an axial load compression mechanism, separating the vertebra into an anterior and a posterior fragment. These fractures can present varying degrees of instability to compression force, depending on the extension of the vertebral body injury, the same occurring with stability to flexion forces, which can be maintained or reduced, depending on the degree of the injury. The fractures are characterized by injuries of the superior disc, compression fractures, fracture of the superior terminal plate, and coronal fracture of the vertebral body. Disc material and fragments of the terminal plate are displaced between the two main fragments and the anterior fragment of the vertebral body is displaced to the front. The exact incidence of pseudoarthrosis following this type of fracture is unknown. Persistent pain after conservative treatment can be caused by undiagnosed pseudoarthrosis. It is possible to treat these coronal split fractures conservatively, through rest and the use of immobilizing orthoses until consolidation occurs, or surgically through fixation of the vertebral segment with pedicle screws.[1,2,3]

Classification of spinal fractures is based on the fact that the morphopathology of the injury indicates the force or momentum applied to the vertebral segment. The three basic forces that produce traumatic injuries of the vertebral segment are compression, traction, and rotation and thus, the morphology of the fracture allows determination of the pathogenesis of the injury. In split-type fractures the vertebral body is separated in the coronal or sagittal plane and the main fragment presents varying degrees of fracture line deviation, size, and regularity.[4,5]

The objective of this study is to evaluate thoracolumbar coronal split fractures using finite elements, observing the stresses and the displacements of the fragments, for two vertebral body fracture conditions (25% and 50%), discussing the limiting factors in deciding between conservative and surgical treatment.

METHODS

This study evaluates two coronal split fracture situations and was conducted using numerical simulations. In the two analysis cases, the fracture considered was in the first lumbar vertebra (L1). In the first case, the fracture line occurred in the middle of the vertebral body (50%), as can be seen in Figure 1A. In the second simulation, the fracture occurred in the anterior quarter of the vertebral body (25%), as shown in Figure 1B. The region was chosen because it is an area of the spine where most fractures occur, according to a study by Magerl and Engelhardt.[6] Because this is a numerical study, it did not require Institutional Review Board approval.

The model was defined using Ansys finite element software. First, the properties of the materials were defined. These values were taken from Kumaresanet et al.[7] and are shown in Table 1. To simplify the analysis and based on the assumption that the elasticity modulus for the ring and nucleus of the intervertebral discs are equal, we took the mean of the Poisson's ratio of the two regions of the disc, resulting in a value of 0.45.

The L1 vertebra was characterized with less resistance than the other vertebrae. Thus, it was assigned a modulus of elasticity value and Poisson's ratio of 0.01 MPa and 0.49, respectively. To maintain the simplicity of the analysis, all materials were considered as isotropic.

The region of the fracture was considered to be in friction with the bodies in its contact zone. However, the remaining contacts between the components were established as bonded. Contact friction was assumed by the fact that the broken body was not connected to the rest of the anatomical structure, in addition to restricting penetration between solids and incorporation of the normal tangential forces between surfaces. The friction coefficient was arbitrated with a value of 0.01, as observed in other biomechanical studies.[7,8]

Thus, a compressive load of 1000N located on the upper surface of vertebra T11 was defined. The restriction of the element was imposed on the lower surface of the fourth lumbar vertebra (L4). An illustration of this stage can be seen in Figure 2, in which the letter "A" symbolizes the fixed area and the letters "B" and "C" the force applied to the structure.

Next, the generation and refinement of the finite element mesh was carried out. Refinement is extremely important since an efficient computational refinement is fundamental to solving the differential equations, especially when there is a large number of variables involved.[9] The mesh was defined in the vertebrae from T11 to L4 and the T11-T12 and L3-L4 discs, all with first order quadrilateral formulation and an element size of 2 mm, as can be seen in Figure 3.

Table 1. Mechanical properties of the materials.[7]

	Modulus of elasticity (MPa)	Poisson's ratio
Cortical bone	10000	0.29
Trabecular bone	100	0.29
Ring of the intervertebral disc	3.4	0.40
Nucleus of the intervertebral disc	3.4	0.49

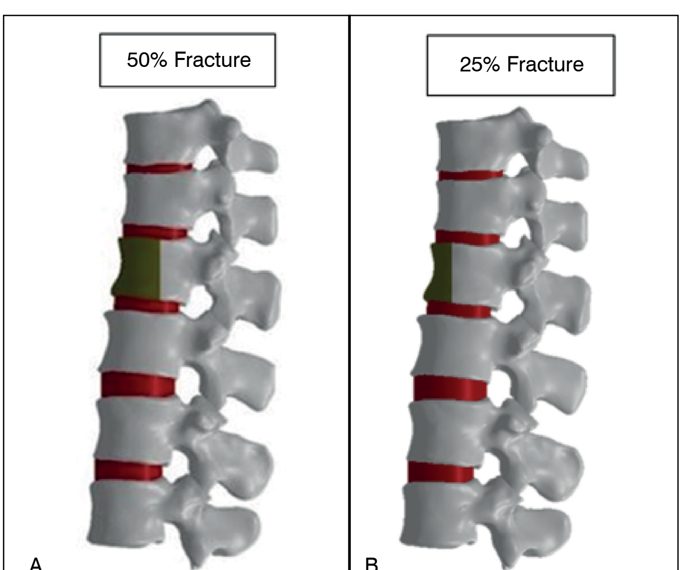

Figure 1. Fracture area in half of the body 50% (A) and in the anterior 25% of the body (B).

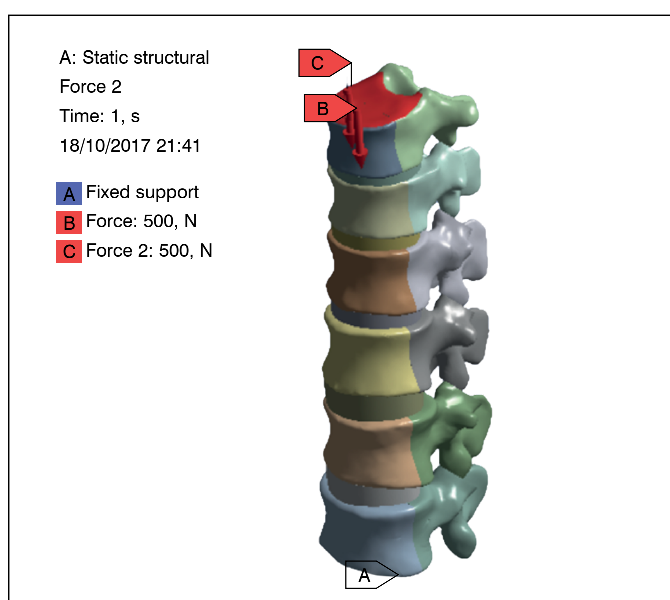

Figure 2. Application of force and definition of the surrounding conditions.

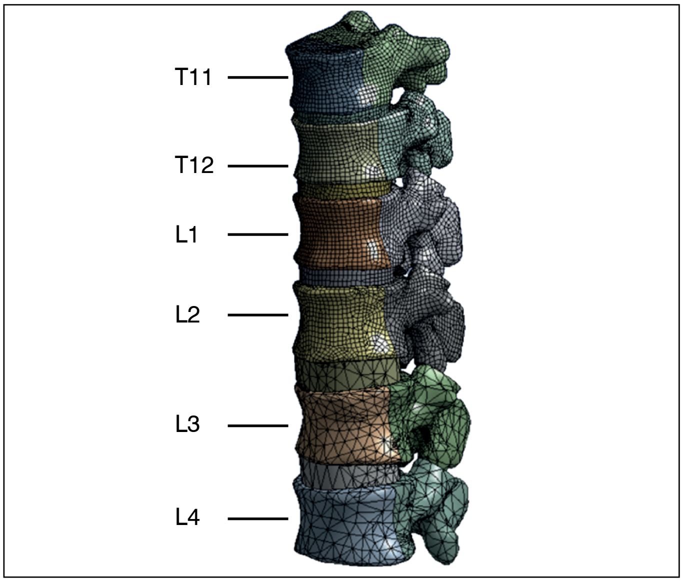

Figure 3. Mesh of the anatomical structure.

RESULTS

Based on the information provided to the CAE software, the two finite element analyses could be processed. The maximum stress values found can be observed in Table 2.

Figures 4A and 4B show the location of the maximum and minimum stress of the simulation of the 50% and 25% fractures, respectively. The simulations demonstrated, therefore, that the greatest stress occurs in portions of the L1 facet joints when there is a split fracture with a 50% vertebral body fracture line and in the lower portions of the L2 facet joints when the fracture occurs in the anterior 25% of the vertebral body.

From this, one can see the axial deformation that has occurred in vertebra L1 in both simulations. The differences in the axial deformation values between the broken frontal region and the fixed body of the vertebra is equal to the distancing between the bodies. Figure 5 illustrates the extraction of the axial deformation values generated in vertebra L1 in the 50% vertebral body fracture simulation. Figure 6 shows the extraction of the axial deformation values in vertebra L1 that occurred in the 25% anterior vertebral body fracture simulation.

Table 3 presents the distancing between the fragments and the rest of the vertebral bodies.

DISCUSSION

This study evaluated thoracolumbar coronal split fractures using finite elements, observing the stresses and the displacements between the fragments for two vertebral body fracture conditions (25% and 50%). In the 50% vertebral body fracture case, the facet joint area of the L1 vertebra was more overloaded. In the fracture that occurred in the anterior quarter of the vertebral body, the greatest stress value was observed in the facet joints of vertebra L2. Accordingly, we observed that the lesser the injury to vertebra L1, the better the distribution of loads to the other vertebrae. Thus, even though it is fractured, the highest level of stress can occur in another undamaged region. Therefore, when the fracture occurs more posteriorly along the body, the facet joint region becomes more overloaded. In the two fracture simulations, the minimum von Mises stress value was obtained in the facetary region of the fourth lumbar vertebra (L4). Analyzing the results and emphasizing that the same boundary conditions and considerations were imposed on both cases, the 50% vertebral body fracture had a maximum von Mises stress 43% greater than the fracture in the anterior quarter of the vertebral body (25%).

In the evaluation of axial displacement in the simulations, the greatest displacement of the fractured body in relation to the part connected to the rest of the structure was observed in the 50% vertebral body fracture. Also, contrary to what we observed in our analysis of the 50% vertebral body fracture, there was no axial displacement of the lower part of the vertebra in the 25% anterior vertebral body fracture. This may explain the reason why in some cases there is invagination of the intervertebral disc, making consolidation of the fracture difficult. There would probably have been a greater opening if the case had been considered in a dynamic

Table 2. Maximum stress values found in the analysis.

	Maximum von Mises stress (MPa)
50% Fracture	264.88
25% Fracture	151.16

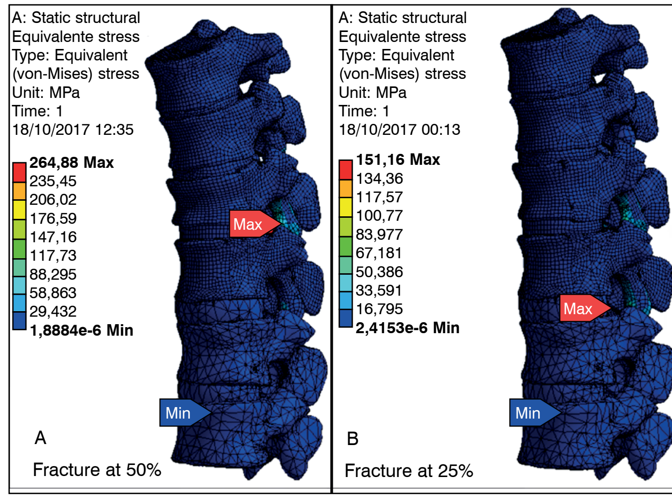

Figure 4. Von Mises stress values obtained.

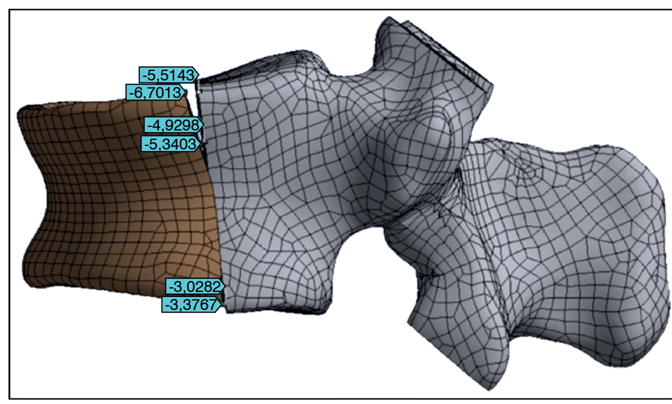

Figure 5. Observation of the axial deformation values in the region with fracture of half of the vertebral body (50%).

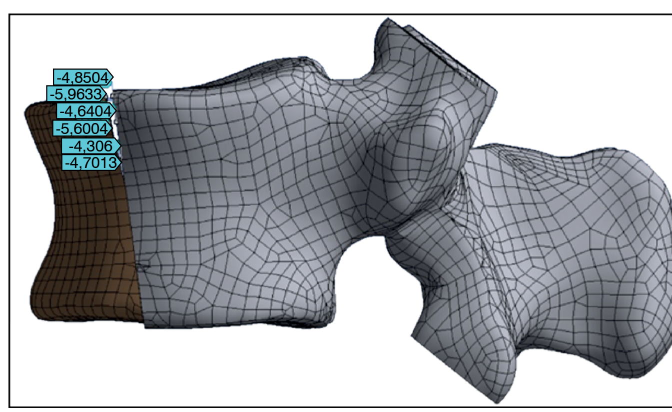

Figure 6. Observation of the axial deformation values of the 25% fractured region.

Table 3. Values found in the axial deformation of vertebra L1.

	Description	Broken portion axial deformation (mm)	Fixed body axial deformation (mm)	Difference (mm)
50% Fracture	Vertebra L1	6.7013	5.5143	1.1870
		5.3403	4.9298	0.4105
		3.3767	3.0282	0.3485
25% Fracture	Vertebra L1	5.9633	4.8584	1.1049
		5.6004	4.6404	0.9600
		4.7013	4.3060	0.3953

analysis or even if the coronal fracture had occurred with a larger portion of the vertebral body.

In medical practice, the treatment objective for these fractures is to restore patient function, facilitating nursing care and preventing additional deterioration. The advantage of the non-surgical treatment method has been in preventing surgical morbidity, such as infection, iatrogenic neurological lesion, implant failure, and anesthesia complications.[9-11] Multiple studies have not succeeded in demonstrating the functional benefits of surgical versus non-surgical treatment of stable injuries.[12,13] Surgical management is associated with better kyphosis correction, but with similar postoperative pain and functional outcomes.[14] It is imperative that non-surgical treatment be closely monitored, as there is a potential for progression of the deformity.[15,16]

In the spine, biomechanical studies are important both for understanding the physiopathology of injuries and for developing prevention and treatment strategies. Usually these studies are conducted using in vitro experiments applied to spinal segments obtained from cadavers. Studies of live subjects provide more reliable and closer to reality information. However, ethical aspects and stricter legislation demand a reduction in the use of models that involve live animals. Computational vertebral models designed using the finite element method facilitate the investigation of the bone component of the spine, permitting more elaborate tests than those possible in in vitro experiments. Due to the relative anatomical simplicity of the vertebra, validation of these computational models is easy when compared to intervertebral disc and vertebral segment models.[16,17] With the technological advances in imaging examinations and computational resources, the possibility of creating highly specific models based on the characteristics of the individual patient is anticipated.

CONCLUSION

Through the numerical simulations analyzed, we were able to evaluate the behavior of thoracolumbar coronal split fractures for the circumstances imposed on the model (25% and 50%) in relation to stresses and deformations.

It has been estimated that fractures of half the vertebral body (50%) treated non-surgically will have a more difficult consolidation than fractures which are located anteriorly to the middle of the vertebral body (25%), since the displacements presented are greater, explaining a greater rate of pseudoarthrosis when treated conservatively.

All authors declare no potential conflict of interest related to this article.

CONTRIBUTION OF THE AUTHORS: RAVM contributed to the concept and to the writing of the manuscript. MMG and DG worked on the simulations of the thoracolumbar fractures conducted with the finite models, and writing of the manuscript. ARH, CLI and LFS performed the bibliographical research, the writing and the review of the manuscript, and they contributed to the intellectual concept of the study.

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