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FINITE ELEMENT ANALYSIS OF THORACIC VERTEBRAL STABILITY SUPPORTED BY THE FOURTH SPINE

ANÁLISE DE ELEMENTOS FINITOS DA ESTABILIDADE VERTEBRAL TORÁCICA SUPORTADA PELA QUARTA COLUNA

ANÁLISIS DE ELEMENTOS FINITOS DE LA ESTABILIDAD VERTEBRAL TORÁCICA APORTADA POR LA CUARTA COLUMNA

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ABSTRACT

Objective: In traumatic injuries of the thoracic spine, three variables are analyzed to make decisions: morphology of the injury, posterior ligamentous complex and neurological status; currently the fourth column is not evaluated; our objective was to determine the biomechanical behavior of the spine with a fracture of the fifth thoracic vertebral body when accompanied by a short oblique fracture of the sternum. Methods: An anonymous model of a healthy 25-year-old male was used, from which the thoracic spine and rib cage were obtained; in addition to the ligaments of the posterior complex and the intervertebral discs, four models were simulated. An axial section was made, a load of 400 N was applied, and the biomechanical behavior of each model was determined. Results: The area that suffered the most stress at the vertebral level was the posterior column of T4-T5 (tensile strength of 747 MPa), which exceeded the plastic limit, the load through the ribs was distributed from the first to the sixth (100 MPa), in the sternum the stress increased (200 MPa), the deformity increased to 45 mm. Conclusions: The sternum was a fundamental part of the spine's stability; the combined injury severely increased the stress (8 MPa to 747 MPa) in the spine and exceeded the plastic limit, which generated an instability that is represented by the global deformity acquired (1 mm to 45 mm). ***Level of evidence II; Prospective comparative study.***

Keywords: Spine; Spinal Fractures; Biomechanical Phenomena; Joint Deformities, Acquired.

RESUMO

Objetivo: Nas lesões traumáticas da coluna torácica, três variáveis são analisadas para tomada de decisão: morfologia da lesão, complexo ligamentar posterior e estado neurológico; atualmente a quarta coluna não é avaliada, nosso objetivo foi determinar o comportamento biomecânico da coluna com fratura do quinto corpo vertebral torácico quando acompanhada de fratura oblíqua curta do esterno. Métodos: Obteve-se um modelo anônimo de um homem saudável de 25 anos, do qual foram obtidas a coluna torácica e caixa torácica, além dos ligamentos do complexo posterior e dos discos intervertebrais, foram simulados 4 modelos, foi feito o corte, e foi aplicada uma carga de 400 N e o comportamento biomecânico de cada modelo foi estendido. Resultados: A área que mais sofreu estresse ao nível vertebral foi a coluna posterior de T4-T5 (resistência à tração de 747 MPa), que ultrapassou o limite plástico, a carga pelas costelas foi distribuída da primeira à sexta (100 MPa), no esterno a maior tensão (200 MPa), a deformidade maior que 45 mm. Conclusões: O esterno foi a peça fundamental na estabilidade da coluna, a lesão combinada aumentou severamente o estresse (8 MPa a 747 MPa) na coluna e ultrapassou o limite plástico, o que mantém uma instabilidade que é representada pela deformidade global adquirida (1 mm a 45 mm). ***Nível de evidência II; Estudo prospectivo comparativo.***

Descritores: *Coluna Vertebral; Fraturas da Coluna Vertebral; Fenômenos Biomecânicos; Deformidades Articulares Adquiridas.*

RESUMEN

Objetivo: En las lesiones traumáticas de la columna torácica se analizan tres variables para tomar decisiones: morfología de la lesión, complejo ligamentoso posterior y estado neurológico; actualmente no se evalúa la cuarta columna, nuestro objetivo fue determinar el comportamiento biomecánico de la columna con una fractura del quinto cuerpo vertebral torácico cuando se acompaña de una fractura oblicua corta del esternón. Métodos: Se utilizó un modelo anónimo de sexo masculino sano de 25 años de edad, del cual se obtuvo la columna torácica, y la caja torácica, además se le agregaron los ligamentos del complejo posterior y los discos intervertebrales, se simularon 4 modelos a los cuales se les realizó un corte axial, se aplicó una carga de 400 N y se determinó el comportamiento biomecánico de cada modelo. Resultados: La zona que más estrés sufrió a nivel vertebral fue la columna posterior de T4-T5 (resistencia a la tracción de 747 MPa), la cual superó el límite plástico, la carga a través de las costillas se distribuyó de la primera a la sexta (100 MPa),

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en el esternón el estrés aumentó (200 MPa), la deformidad aumentó a 45 mm. Conclusiones: El esternón fue parte fundamental en la estabilidad de la columna, la lesión combinada incrementó severamente el estrés (8 MPa a 747 MPa) en la columna y este superó el límite plástico, lo que generó una inestabilidad que se representa por la deformidad global adquirida (1 mm a 45 mm). ***Nivel de evidencia II; Estudio prospectivo comparativo.***

Descriptores: *Columna Vertebral; Fracturas de la Columna Vertebral; Fenómenos Biomecánicos; Deformidades Adquiridas de la Articulación.*

INTRODUCTION

Traumatic fractures of the thoracolumbar spine represent about 90% of spinal injuries, and the T1-T10 location represents 16%;[1-3] the injury combined with sternum fractures is rare. However, they confer a significant risk of spinal instability; it occurs between the second and fourth decades of life, mainly in men in a 4:1 ratio, being mainly caused by traffic accidents and suffering stresses in flexion--compression/flexion, distraction/flexion-rotation; this type of injury notably increases morbidity and mortality.[4] Until the investigation, there was no treatment of choice for this type of injury, which is why they can be managed with multiple modalities (conservative, spinal fixation, sternal fixation, or combined fixation).

MATERIALS AND METHODS

This study was performed after obtaining the institutional review board approval from the Research Ethics Committee of Hospital General del Estado "Dr. Ernesto Ramos Bours" [ID: 07-22-01].

The geometry was obtained from a computed tomography (CT) of the thoracic spine of a 25-year-old anonymous healthy male; from this CT, the vertebra and rib cage were obtained, obtained from the Embodi3D website in STL format; these were adapted for simulation in SolidWorks 2020, where the intervertebral discs, including the *annulus fibrosus* and *nucleus pulposus*, were also drawn and added to the model.

For the healthy patient simulation, the mesh model consists of a complete mesh consisting of 565,314 three-dimensional elements, 176,683 surface faces, and 4,955 edges (Figure 1).

The boundary conditions that were applied in the 4 study cases were the following: a load of 400N in the upper part of the vertebral body, as well as a condition of fixed restriction in the lower face of the T12 vertebra, necessary to be able to solve the simulation, as a reference point.

Ligamentous structures were modeled as flexible-type couplings and, in some cases, rigid-type couplings, as appropriate; this includes tension band ligaments (*supraspinatus*, *interspinous*, yellow ligament, facets), vertebral (anterior longitudinal and posterior longitudinal), costospinal (radial and costovertebral) this type of coupling allows the physical and mechanical contribution of the ligaments to be taken into account in the simulation, with the advantage that it is not necessary to draw them or mesh them in the model, simplifying the model and making it more efficient for manipulating it, without losing mechanical reliability in the results.

The properties of the materials used in the model were: for the bone structures, a Young's Modulus of 12 GPa, a Poisson's ratio of 0.3 and a density of 1560 Kg/m3, for the fibrous ring of the intervertebral discs, an elastic modulus of 0.55GPa, a Poisson's ratio of 0.3 and a density of 1000 Kg/m3 and the *nucleus pulposus* an elastic module of 1 MPa, a Poisson's ratio of 0.49 and a density of 1000 Kg/m3

For the fractured cases, the geometry of the structure was modified to simulate a fracture in the T5 vertebra; 50% of the geometry was cut; in the same way, to simulate the case of a fractured sternum, the geometry of the sternum was modified to simulate an oblique fracture similar to the one that occurs in some patients with a sternum fracture, it is worth mentioning that the cut in the geometry was made in the area of the sternum that presents a greater concentration of stresses in the simulations of a healthy patient.

RESULTS

From a model of 565,314 three-dimensional elements, 176,683 superficial faces, and 4,955 edges to which a load of 400 N was applied to the upper platform of T1 in the four models (healthy, T5 fracture, sternal fracture, and combined fracture of sternum- T5) and later using the COMSOL system, the following results were obtained:

Healthy Model A (Figure 2): The area that presented the most stress at the vertebral level was the anterior column of T6 (compression force) (Figure 3) (8 MPa); the load on the rib cage was distributed mainly by the first and second arch (14 MPa), in the sternum, the union between the second and third rib is the area that was most requested (strength in compression) (9 MPa), the deformity that it presented was 1 mm.

Model B T5 vertebral column fracture: The area that presented the most stress at the vertebral level was the posterior column of T5 (tension force) (Figure 4) (35 MPa) in addition to being overloaded from T6-T9 (15 MPa), the load through the ribs was modified and lowered by the seventh and eighth (18 MPa), in the sternum the union between the sixth and seventh rib was the area that presented the most stress (60 MPa), the deformity increased to 5.53 mm.

Model C T5 vertebral column fracture plus sternal fracture (Figure 5): The area that suffered the most stress at the vertebral level was the posterior column of T4-T5 (force in tension) (Figure 6) (747 MPa), which exceeded the plastic limit, the load through the ribs was distributed from the first to the sixth (100 MPa), in the sternum the stress increased (200 MPa), the deformity increased to 45 mm.

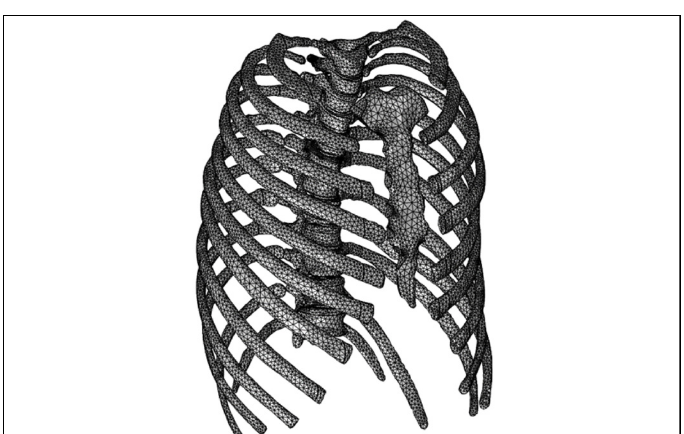

Figure 1. Full mesh healthy model.

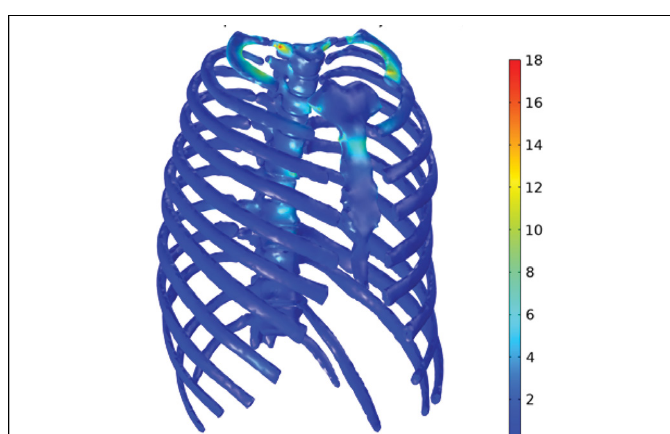

Figure 2. Model A.

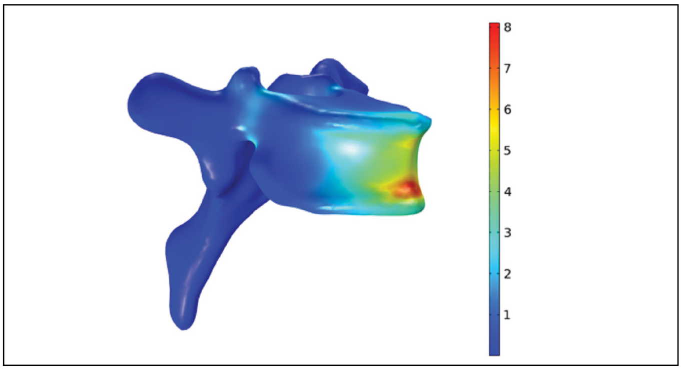

Figure 3. Model A, effort at T6.

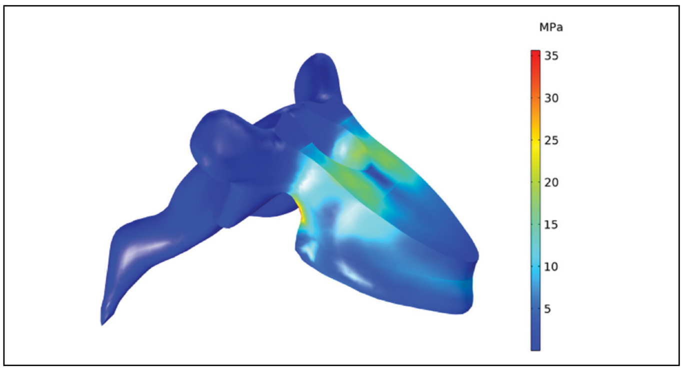

Figure 4. Model B, effort in T5.

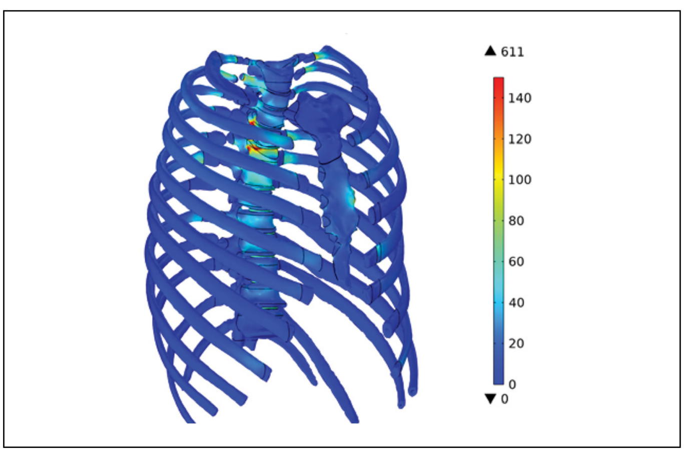

Figure 5. Model C.

Model D Isolated sternal fracture: The area that suffered the most stress at the vertebral level was the anterior column of T4-T8 (compression force 10 MPa). The load through the ribs was distributed by the first (20 MPa); in the sternum, the load decreased due to the loss of the fourth column (9 MPa), and the deformity presented was 1.27 mm.

DISCUSSION

The spinal column has four functions (protecting the nervous tissue, capacity to distribute loads, giving spinal morphology, and allowing movement) which are intertwined to allow an adequate function; stability is included within the mechanical capacity to distribute loads which refers to the ability of the spine to tolerate physiological loads and not a present deformity, pain, or neurological compromise, when this is not fulfilled it is considered instability.[5-7]

The vertebra have inherent stability due to their shape, joint facets, ligaments, and muscles; this ability is enhanced by the rib cage (ribs-sternum).

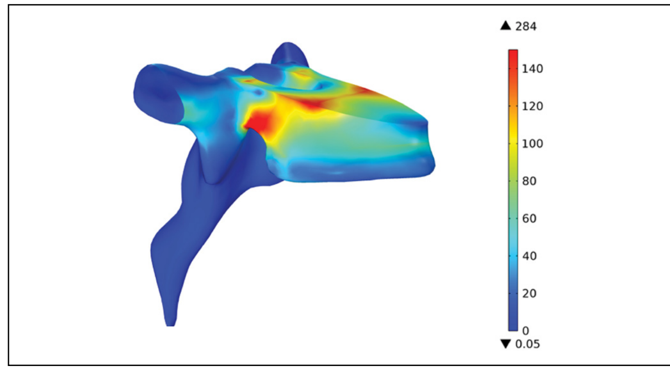

Figure 6. Model C, effort in T5.

A clear example of what has been described above is that the movement in the sagittal plane of the thoracic functional unit in the absence of the chest allows an average of 4-5^{o}, this being a global movement (T1-T12) of 40-50^{o}, and keeping in mind the chest thoracic, the global movement is on average 7.9^{o} (2.64^{o}-15.64^{o}), this shows the great stability that this complex transmits.[8-9]

The first classification of the columns was described in 1963 by Holdsworth, who divided this theory into two columns and continued for many years, even White- Panjabi in his book Clinical Biomechanics of the Spine 1990 continued to propose the theory of the two columns, however, in 1983 Francis Denis described those three columns give stability and that having an injury to two or more of them should be considered biomechanical instability, which is still valid to this day.[10-14]

However, scientific knowledge has advanced, showing that stability is not only given by static structures such as bone tissue and the capsule-ligament complex but also by muscle insertions in the thoracic region (T1-T10). The rib cage helps in global spinal stability, so an injury to it affects the stable behavior of the spine under physiological loads.[15-17]

In 1993 Berg made a publication where he describes that in the thoracic spine, there is a fourth column which he called the "sternal complex," and has a strut function; this concept has been studied by other authors[18] who have observed that injury to this spine with or without vertebral involvement can generate a kyphotic deformity.[19]

In 2017, Robert Pearse Piggott's working group published those metastases to the sternum also favor kyphotic deformity even without spinal pathology lesions.[16]

When analyzing how the loads are distributed through the four columns, they can be explained as follows:

The anterior and middle column of Denis has compression loads. In contrast, the posterior column is subjected to tension, and the fourth column of Berg supports the strut, increasing the resistance to bending of the rest of the columns, the spine, and the rib cage as a whole. They behave like the second Pauwels column, the anterior region is subjected to compression (75% of the axial load), and another region is subjected to tension (25% of the axial load).

In this way, the importance of the sternum to serve as a strut and limit movements in the sagittal plane was understood.[20-26]

Based on our results, a graph was made (Figure 7) where it was possible to observe that model C behaves more unstable; in addition, the displacement measured in the different models shows a linear behavior between the deformity of the sternum and the fracture of T5 (Figure 8).

Watkins et al. [2005] concluded that the rib cage increases stability in the sagittal plane by 40% and is severely affected in case of sternal injury, our results related.[9]

Most studies conducted in clinical sceneries conclude that although combined injury is rare, there is still no gold standard in therapeutic decisions due to the lack of knowledge of their biomechanical behavior. For this reason, our results provide a great advance for the behavior of these injuries, knowing that the computational models are valid when compared to biomechanical studies due to

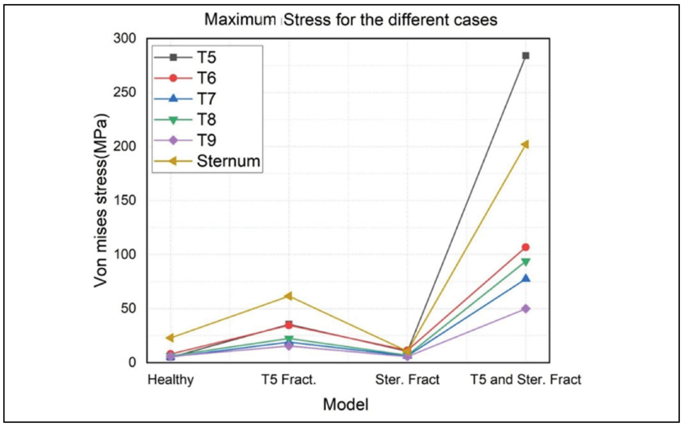

Figure 7. Graph the relationship between the effort (MPa) and models with a load of 400N.

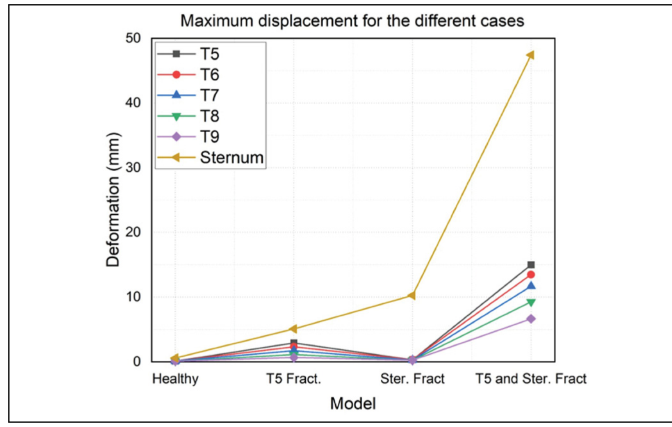

Figure 8. Graph the relationship between the deformation (mm) and models with a load of 400N.

the homogeneity of the sample (same tissue density, same model, and complexity of the same), which reduces the probability of error.

Our study determined that the combined injury [model C] is a severe injury that requires stabilization management to prevent deformity.

CONCLUSION

Based on our study, we determine the sternum was a fundamental part in the stability of the thoracic spine; it functioned as a vertebral buttress and prevented it from collapsing in a sagittal plane, the combined injury severely increased stress in the spine, and this exceeded Its plastic limit, why a generated instability that is represented by the global acquired deformity, based on the results, the scores that help us in the therapeutic decision making should include the fourth column.

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

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