Biomechanics Simulation Report: Finite Element Analysis of a Thoracic Vertebrae

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Abstract: Thoracic vertebrae are situated in the central region of the vertebral column. They connect with the ribs and assist in bearing the body's load. Compression fractures are the most prevalent spinal injury. Treatment involves injecting bone cement into the fracture. Typically, the primary therapy involves injecting bone-cement into the fracture. The project involved analyzing the behavior of 3D models of the fifth thoracic vertebra in Abaqus software using the finite element method. Two models were utilized, one representing healthy bone and the other demonstrating osteoporosis. A load of 300 N was applied on the two vertebrae to simulate body weight. To mimic the result of a fracture followed by kyphoplasty, two spheroids of bone cement were created inside the vertebral body. The osteoporotic bone model showed considerably higher values of stress, strain, and displacement when compared to the normal bone model. The values of strain and displacement decrease with the inclusion of cement spheroids, as well as with the increase of their volume (strain).

I. INTRODUCTION:

At the molecular level, bone is a composite material comprised of collagen and crystalline calcium phosphate salts. Collagen provides toughness, while inorganic salts contribute to the stiffness of the matrix. Two types of bone exist: a denser tissue called cortical bone, located on the outer layer and trabecular bone, the porous inner layer [1].

Each vertebra consists of a vertebral body and a vertebral arch. The vertebral body bears weight. Adjacent vertebrae are separated by fibrocartilaginous intervertebral discs, with the lower one being larger than the upper. The vertebral arch is located posteriorly and is connected to the body by two pedicles. The main components are the two laminae that fuse at the midline. Posteriorly, there is a spinous process and two transverse processes on each side of the arch. Each side has a superior articular process and an inferior articular process. The superior articular process of one vertebra connects with the inferior articular process of the vertebra above it. The vertebrae's arches create the vertebral canal, housing the spinal cord, protective membranes, blood vessels, connective tissue, fat, and spinal nerves [2].

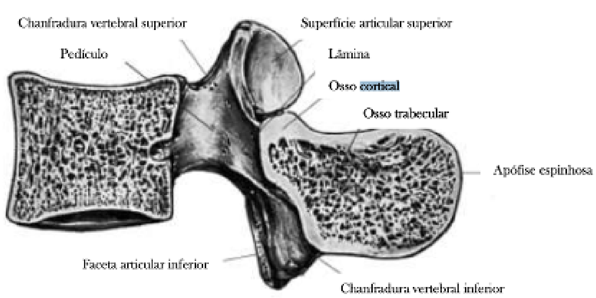

Figura 3.1 – Histologia de uma vértebra adaptado de (Drake et al. 2008).

Thoracic vertebrae are the 12 vertebrae that articulate with ribs. They are characterized by the two partial facets (superior and inferior costal facets), which are on each side of the body. These articulate with the heads of its own rib and of the rib below, respectively. There is also a facet in the transverse process, which articulates with the tubercle of its own rib. The vertebral column supports the body's weight, allows for movement, and protects the spinal cord from injury. Thoracic vertebrae fractures are usually caused by major trauma or, in osteoporotic individuals, by minor trauma [2] and can be classified into three categories: type A - compression injuries without ligament disruption -, type B - distraction injuries, with ligament disruption -, and type C, translational injuries, where the vertebral column is no longer aligned [3].

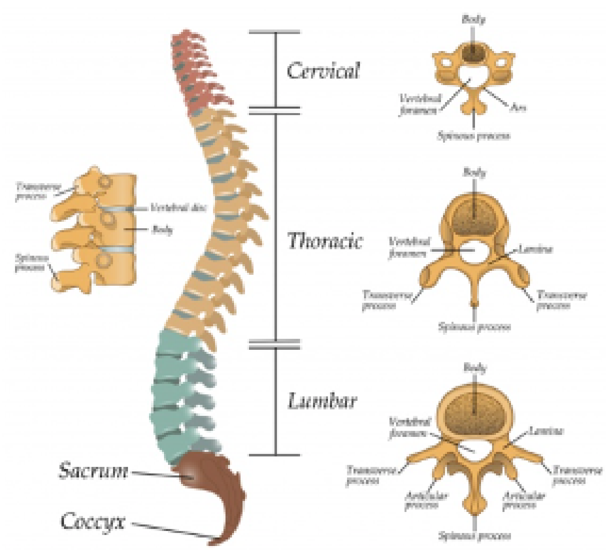

Fig. 2: Representation of the thoracic vertebrae in the human body [4].

Osteoporosis is a condition characterized by decreased bone mass, changes in bone structure, and an increased risk of fractures due to an hormonal-based imbalance between the process of bone creation and bone resorption. This condition represents a significant health issue, with approximately 200 million individuals experience a diminished quality of life [4].

Bone fragility fractures incur significant treatment costs.

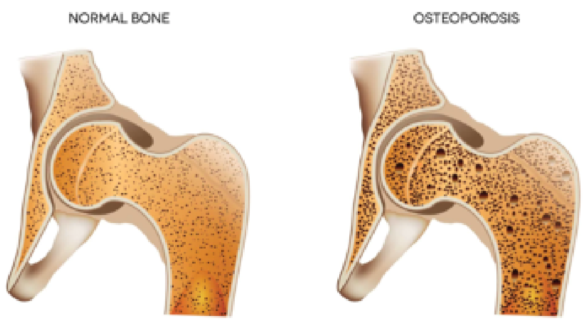

Fig. 3: Comparison between a normal bone and a bone with osteoporosis [5]

Management ranges from immobilization and bracing for minor fractures to surgery for more severe cases. Among the surgical interventions for vertebral fractures, vertebroplasty and kyphoplasty are the most common. In vertebroplasty, bone cement is injected directly into the fracture site. Conversely, kyphoplasty involves inserting a balloon into the vertebra through a tube, inflating it to restore the vertebra to its normal height, and creating a cavity. This cavity is, then, filled with bone-cement. Optionally, two cavities can be created and filled, one on each side of the vertebra.

Polymethyl methacrylate (PMMA) bone-cement is a commonly used material for reinforcing bone in vertebroplasty due to its favorable mechanical and biological properties. These include its bioinert nature, biocompatibility, ease of handling, good mechanical strength, and cost-effectiveness. However, PMMA also presents certain drawbacks, such as its inability to integrate with native bone and regenerate bone tissue. Additionally, its excessive stiffness may contribute to the fracture of adjacent vertebrae.

The finite element method (FEM) is a computational approach used to solve partial differential equations, allowing researchers to simulate complex material interactions in engineering domains like stress analysis, heat transfer, and fluid dynamics. Objects analyzed with FEM are segmented into domains comprising finite elements connected by nodes, forming a finite element mesh. These domains are subdivided into elements, and equations are estimated using variational techniques for each subdomain. Widely applied in structural analysis, mechanical design, and civil engineering, FEM optimizes designs and predicts material behavior under different conditions. By breaking down complex systems, FEM enables accurate predictions and efficient problem-solving across engineering disciplines.

The primary aim of this study is to employ FEM for analyzing the behavior of normal and osteoporotic thoracic vertebrae under vertebroplasty using PMMA bone-cement through simulation in Abaqus® software.

II. Materials and Methods:

In this project, three main values were used to evaluate the model's mechanical behavior. The first one, Von Mises Stress (S), tackles the chances of the material to yield or suffer a fracture, by comparing it to the material "yield limit", the second, displacement (U) indicates the magnitude of movement happening around an "impact point" and the last one, the Strain (E) suffered by the material itself.

A three-dimensional model of a thoracic vertebra was provided by the docents to be evaluated as seen in the image below.

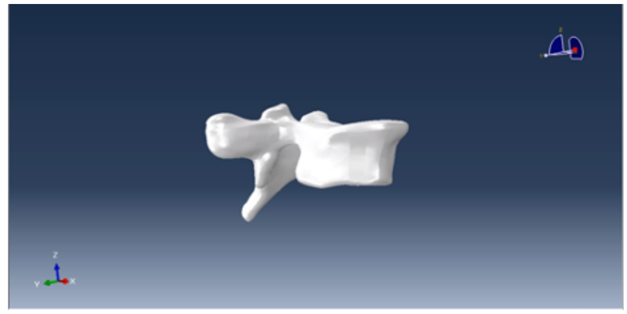

Fig. 4: Final Geometry

Due to the software license provided, a limit of 1.000 nodes was defined as maximum and, therefore, a mesh composed of 994 nodes and 3659 elements was created. In order to respect the aforementioned constraint, the "Global Seeds" properties were altered, with a global size of 10.5, curvature control of 0.1 h/L and minimum size control equal to 0.1 min. Finally, a 4-Node Linear Tetrahedral Model without hybrid formulation was selected.

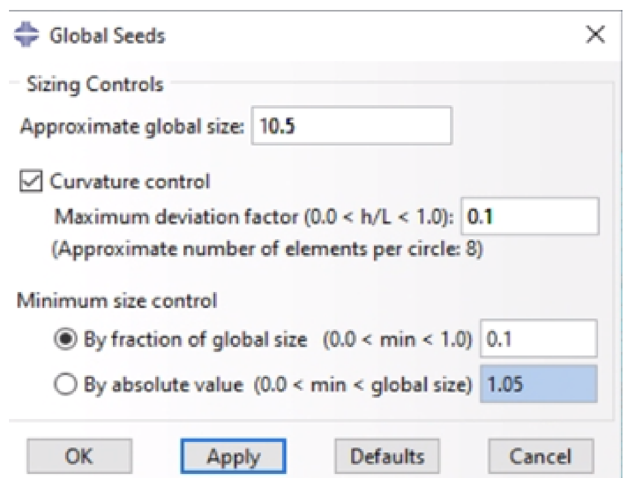

Fig. 5: Settings used on the program

Once the mesh was created, and following the references of S Oliveira, C. & Carneiro [6], the group split the model into four mechanically different regions with separated sets: Cortical, Trabecular, Posterior Elements and Bone End Plate, as seen in figure 6. For each set, properties were assigned for both the healthy bone and for its osteoporotic version following values found in the literature.

Section	Modulus of elasticity E (MPa)		Reference	Poisson's ratio (v)	Reference
	Healthy	Osteoporotic			
Cortical	5000	3350	(Villarraga PhD et al. 2004)	0.3	(Zhang et al. 2010)
Trabecular	100	34	(Zhang et al. 2010)	0.2	(Zhang et al. 2010)
Bone End Plate	1000	670	(Villarraga PhD et al. 2004; Zhang et al. 2010)	0.3	(Villarraga PhD et al. 2004)
Posterior Elements	3500	2345	(Qiu et al. 2006; Pitzen et al. 2002)	0.25	(Teoh & Chui 2008; Rohlmann et al. 2010)

TABLE I: Mechanical properties attributed to the components of the vertebra.

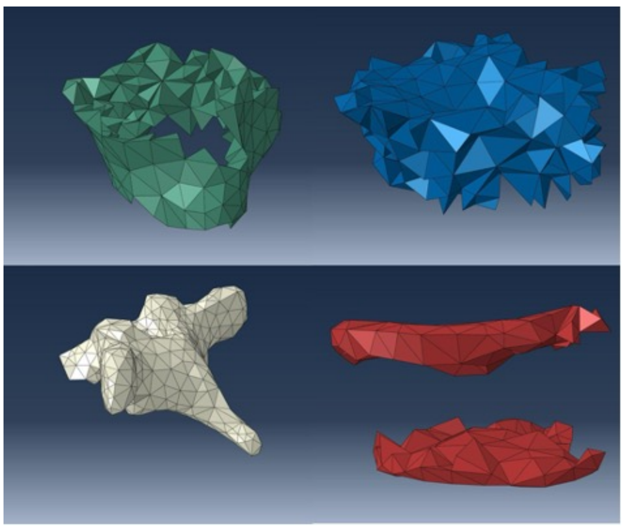

Fig. 6: Images from the material segmentation, from the upper-right to the lower-left: (a) Cortical Segmentation, (b) Trabecular Segmentation, (c) Posterior Elements Segmentation, (d) Bone End Plate Segmentation

A. Load simulation:

With the solid defined, a load of 300 N was applied on the two vertebrae, to simulate an average male adult body size of 100 Kg. This value was chosen following the stipulation for a thoracic vertebra, with its load being of approximately 30% of the body weight. The load was applied on the superior face of the body, while the inferior face was fixed as exemplified on the image below (arrows indicate the force direction, while orange spots are fixed).

B. Bone-cement simulation:

Lastly, to evaluate the effect of a vertebroplasty on the bone's mechanical properties, two different cementation approaches were pursued using the same Poly(methyl methacrylate) (PMMA) material on "spheroids-like" regions contained inside the vertebrae model with values varying from 10% - 20% of the total vertebrae body volume. Like the bone's properties, the values of elasticity moduli and Poisson's coefficient were used according to the bibliography followed by the group.

Material	Modulus of elasticity E (MPa)	Poisson's ratio (v)	Reference
PMMA	3500	0.3	(Li & Lewis 2010)
HAp + AS-Sr	2	0.2	(Zhang et al. 2010)

TABLE II: Mechanical properties attributed to the simulated bone-cement.

Due to time and processing limits, the cementation method simulated is referred to as Unipedicular since only a single "vertebral body pedicle" is introduced into the bone, causing, therefore, space for only one cement spheroid. Many articles tackle the difference between using a unipedicular vs a bipedicular approach and its effect on mechanical stability and other properties. In order to create those spheroids, manual selection of the mesh was used to simulate the replacement of the bone with PMMA and its volume, in percentage of the vertebrate body, evaluated, achieving 9.66 % and 20.69%. The replacement of these parts in the vertebrate body is represented in the picture below.

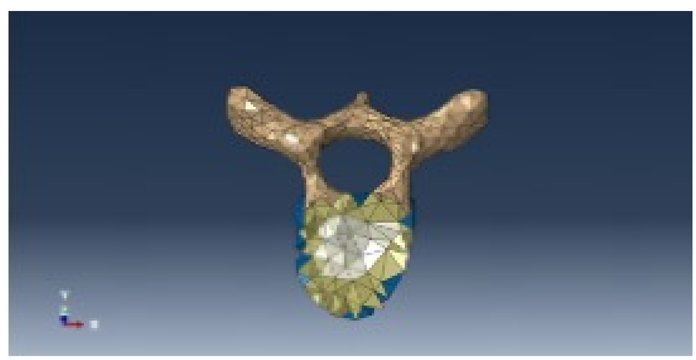

Fig. 7: Images from the PMMA replacement, showing the 20.69% volume replacement.

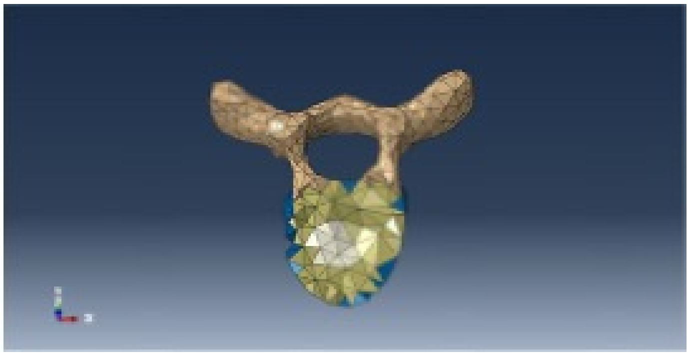

Fig. 7: Images from the PMMA replacement, showing the 9.66% volume replacement.

III. Results:

A. Healthy vs Osteoporosis

In order to further develop the group's analysis on the bone model, it is important to understand its "normal" behavior.

I. Healthy Model: When subjected to a 300N force, the model presented a Von Mises Stress (S) in average of about 382 MPa in the region of connection between the Cortical Wall and the Lower End Bone Plate, as seen in the images below.

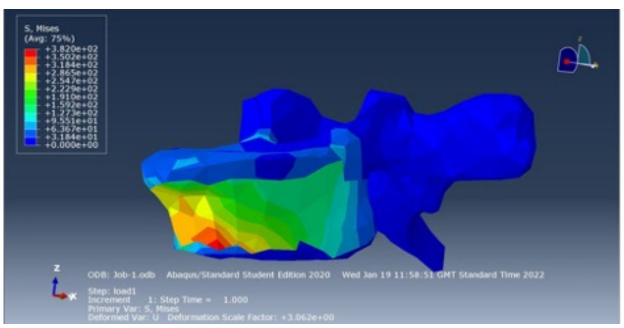

Fig. 8: Three Dimensional view of Von Mises Stress distribution along the healthy model

Analyzing the displacement behavior, the biggest movements happen on both ends of the model, namely the tip of the Posterior Element with 2.5mm and the tip of the upper Bone End Plate, with 1.87mm.

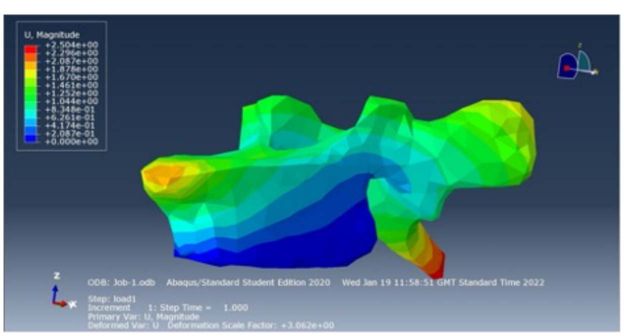

Fig. 9: Three Dimensional view of the magnitude of the Displacement distribution along the healthy model

Lastly, the strain is approximately constant throughout the frontal part of the model, distributing itself evenly on the Cortical segmentation and Both End Plates with a maximum principal value of around 0.03 There is, however, a negative gradient the closer it gets to the Posterior Elements.

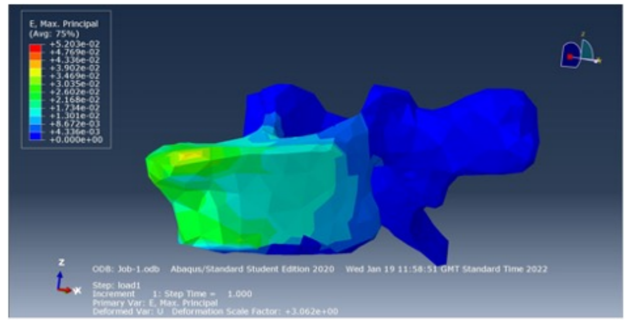

Fig. 10: Three Dimensional view of the maximum Strain suffered along the healthy model

By comparing the results of the regions with bigger stress and displacement, the group interpreted that two situations might be in place: the first being that the results were probably affected by the rather simple mesh modelation, leaving "weak points" in the conjunction between different segments and the second, the hypothesis that these areas are indeed naturally weaker points of the bone.

II. Osteoporotic model: As expected, the osteoporotic bone presented a much higher stress, with an average value of 402 MPa maintaining its spatial distribution.

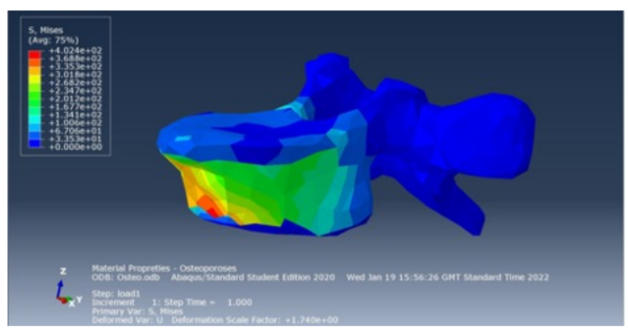

Fig. 11: Three Dimensional view of Von Mises Stress distribution along the osteoporotic model

The same behavior was observed when comparing the displacement with values of 4.4mm and 2.93mm following the previously mentioned spatial scattering.

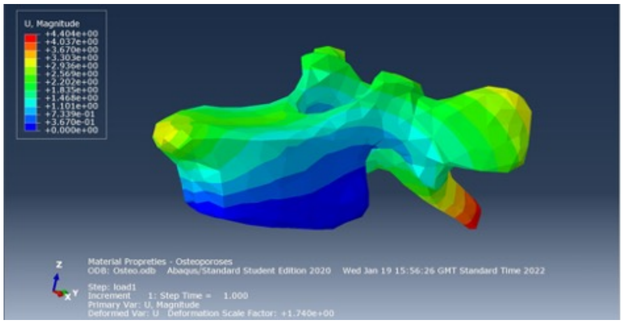

Fig. 12: Three Dimensional view of the magnitude of the Displacement distribution along the osteoporotic model

And lastly, although the distribution seems to be overall maintained, both the peak value - on the tip of the upper Bone End Plate - and its surroundings present a slightly bigger strain value

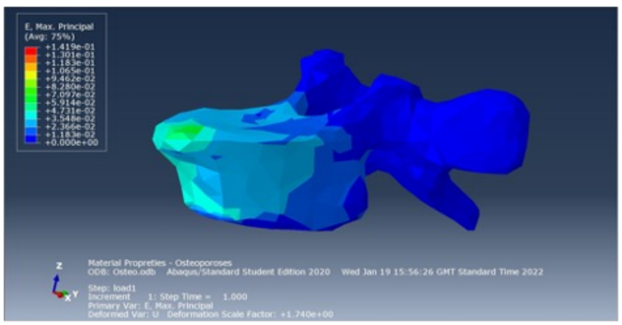

Fig. 13: Three Dimensional view of the maximum Strain suffered along the osteoporotic model

The results were summarized on the following table, it is important to mention, however, that those are much higher than expected from the literature, which could be due to the model being of a thoracic vertebra while the literature tackles lumbar vertebrae.

	Healthy Bone	Osteoporotic Bone
Maximum Point of Von Mises Stress (S - MPa)	3.82*E+2	4.04*E+2
Displacement (U - mm)	2.5 - 1.87	4.4 - 2. 93
Strain (E)	3.46*E-2	4.73*E-2

TABLE III: Comparison between values achieved on the Healthy vs Osteoporotic Bone Model

IV. Discussion:

A. *How different percentages of cracks impact on healthy bone properties*

As mentioned in the previous sections, the percentage of the cracks simulated by replacing a volume of 9.66% and 20.69% of the vertebrate body by PMMA. The PMMA has a Young's Modulus of 3500 MPa, much higher than the Young's Modulus of the trabecular bone it is replacing. As a result, an increasing amount of PMMA replacement leads to lower von mises stress, lower strain and a lower displacement values. In short, the PMMA makes the bone more resilient. Withstanding the same charge, yet having less deformation. A Table with the maximum values of stress, strain and displacement is presented below:

	9.66 % PMMA	20.69% PMMA
Maximum Point of Von Mises Stress (S - MPa)	2.96*E+2	2.75*E+2
Displacement (U - mm)	1.81	1.68
Strain (E)	5.84*E-2	5.84*E-2

TABLE IV: Comparison between values achieved with 9.66% and 20.69% PMMA bone-cement.

The spatial distribution of the strain, stress and displacement is fairly similar to the one without bone-cement. This isn't surprising, given that the shape of the vertebra in question is similar. This can be seen by the pictures bellow that illustrate the behavior of the three discussed mechanical characteristics.

B. *How different percentage of cementation impact on osteoporotic bone properties*

In terms of analyzing the influence of different cementation percentages on the mechanical properties of osteoporotic bone, the distributions of the following variables, von mises stress (S), displacement (U) and strain (E), were studied and the images below were obtained. The different cementation percentages used were 10% and 20% of the vertebrate bone volume.

As we can see from the figure 14, at 10% the highest value of the stress parameter is 296,3 MPa. The highest value of displacement is 2,718 mm and 0,1058 corresponds to the highest strain parameter value. Additionally, in strain, there aren't regions with the maximum values. In the case of the displacement parameter, the maximum regions are in the upper zone, more specifically on the Posterior Elements and, in the stress parameter, the maximum regions are located in the middle zone, namely the cortical zone.

At 20%, the behavior is very similar and further information can be seen in figure 15 . However, 283,8 MPa, was the maximum value recorded to stress, 2,489 mm was the highest value of displacement and, 0,1059 corresponds to the highest strain value. In two parameters, in particular, the stress and the displacement, the maximum values at 20% are smaller than in the 10% case, this means that with the increase of the cement percentage, the maximum values of these parameters decrease. On the other hand, in the strain, although the difference is minimal, the highest value occurs in the case where 20% cementation was used.

Furthermore, compared with the osteoporotic models, previously presented, it is noticeable that the stress decreases with the presence of the cement, such as in the displacement

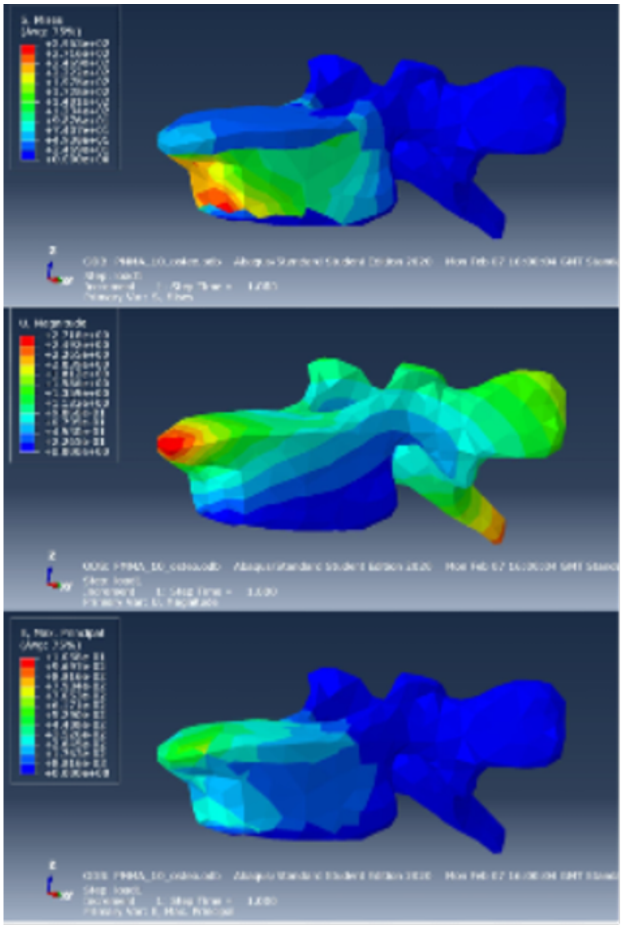

Fig. 14: Effect of the presence of 10% cementation in osteoporotic bone, on the parameters of stress, strain and displacement, obtained by simulation in the Abaqus software

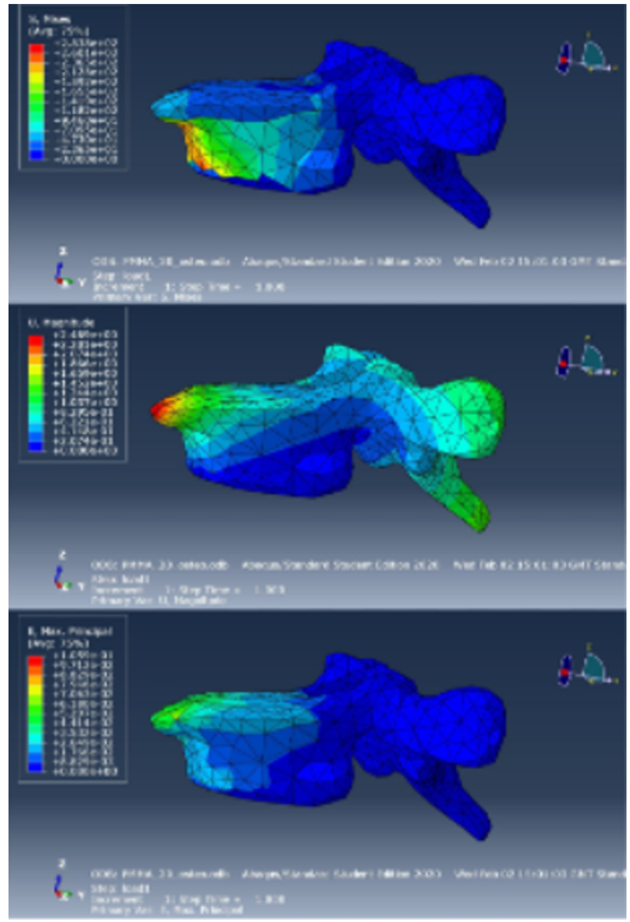

Fig. 15: Effect of the presence of 20% cementation in osteoporotic bone, on the parameters of stress, strain and displacement, obtained by simulation in the Abaqus software

case and, finally in what regards to the strain, the same happens. However, this decrease is more noticeable in the case of stress. This can be explained by the fact that stress is defined by the probability of the material yielding or suffering a fracture and, in the presence of osteoporosis, the material is much more susceptible to yielding or suffering a fracture, than in the case where cement is applied. The table w below shows a summary of the data obtained regarding the comparison between the values of each parameter and the different percentages of cementation tested.

	10% Cementation	20% Cementation
Maximum Point of Von Mises Stress (S - MPa)	296.3	283.8
Displacement (U - mm)	2.72	2.49
Strain (E)	0.106	0.106

TABLE V: Maximum values of each parameter evaluated for each of the tested cementations.

V. Conclusion

A model of the fifth thoracic vertebra was studied as to its mechanical properties with normal or reduced density, and with and without the inclusion of bone cement. It was concluded that an osteoporotic vertebra experiences higher stress, strain and displacement, as was expected, since it is more fragile than a normal bone. As to the bone cement injection, it decreases the strain, stress and displacement values. Further studies could include a simulation with more nodes, to provide better data, as well as an analysis of the properties of a fractured bone without bone cement

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