Stress Changes in an Osteoporotic Column – A Finite Element Study

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Dedico este trabalho à minha família e namorada

Resumo

A coluna vertebral é o eixo central que suporta o peso do corpo humano, garantindo em simultâneo a estabilidade necessária para a manutenção da postura e a flexibilidade essencial para os movimentos do tronco. Ao longo da vida os componentes da coluna vão sofrendo alterações degenerativas que afetam as suas funções. A osteoporose é a patologia degenerativa da coluna mais frequente, condicionando um maior risco de fraturas vertebrais e consequente dor lombar e limitação na realização de atividades do quotidiano.

O presente trabalho incide sobre o impacto da osteoporose na distribuição de tensões na coluna vertebral degenerada quando esta é submetida a uma carga e sobre a relação entre as alterações observadas e o risco aumentado de fraturas vertebrais nestes doentes.

Para melhor se compreenderem as consequências da osteoporose na coluna vertebral, recriou-se o comportamento biomecânico da coluna vertebral em duas situações – indivíduo saudável *versus* indivíduo com osteoporose - num modelo tridimensional e posteriormente aplicaram-se três diferentes condições de suporte de carga. Por fim, procedeu-se a um estudo numérico baseado no método de elementos finitos de forma a comparar o impacto da carga em cada uma das realidades.

Os resultados obtidos demonstraram uma inversão da distribuição dos valores de *von Mises stress* nas vértebras do modelo osteoporótico, com um aumento destes valores no osso cortical, particularmente nos limites das superfícies vertebrais, e uma redução dos mesmos no osso trabecular. Estas alterações corroboram a remodelação arquitetónica que carateriza a osteoporose e a sua relação com um risco incrementado de fratura vertebral e de sintomatologia potencialmente limitante para os doentes em causa.

Palavras-chave: osteoporose, coluna vertebral, fratura vertebral de compressão, von Mises stress, biomecânica , análise de elementos finitos.

Abstract

The vertebral column is the central axis that supports the weight of the human body, while ensuring the stability necessary for maintaining posture and the essential flexibility for trunk movements. Throughout life the components of the spine undergo degenerative changes that impair its functions. Osteoporosis is the most frequent degenerative pathology of the spine, leading to a greater risk of vertebral fractures and consequent low back pain and limitation in carrying out daily activities.

The present work focuses on the impact of osteoporosis on the distribution of stress in the degenerated spine when it is subjected to load and on the relationship between the observed changes and the increased risk of vertebral fractures in these patients.

To better understand the consequences of osteoporosis on the vertebral column, the biomechanical behaviour of the spine was recreated in two situations - healthy individual versus individual with osteoporosis - in a three-dimensional model and three different load-bearing conditions were subsequently applied. Finally, a numerical study was carried out based on the finite element method in order to compare the impact of the load on each one of the realities.

The results obtained showed an inversion of the distribution of *von Mises stress* values in the vertebrae of the osteoporotic model, with an increase of these values in cortical bone, particularly at the edges of vertebral surfaces, and a reduction of these values in trabecular bone. These changes corroborate the architectural remodelling that characterizes osteoporosis and its relationship with an increased risk of vertebral fracture and potentially limiting symptoms for the patients with this pathology.

Keywords: osteoporosis, vertebral column, vertebral compressive fracture, von Mises stress, biomechanics, finite element analysis.

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Abbreviations

AR	Axial Rotation
BMD	Bone Mineral Density
BMI	Body Mass Index
C	Cervical
CT	Computed Tomography
DEXA	Dual-energy X-ray Absorptiometry
FEA	Finite Element Analyses
FF	Forward Flexion
L	Lumbar
LB	Lateral Bending
MHT	Menopausal hormone therapy
T	Thoracic
VCF	Vertebral column fractures

Chapter 1

Introduction

The present chapter addresses the context of degenerative pathology of the vertebral column, the goals of the work developed and the structure of the document.

1.1 Context and Motivation

Osteoporosis consists in a pathology characterized by a defect of the bone anabolism, predominant in the elderly. This disease results in an imbalance between bone-forming osteoblasts and bone-resorbing osteoclasts, with consequent diminished bone mass, microarchitectural deterioration and increased risk of bone fractures. This is the most prevalent bone condition in the World and estimations predict a doubling of the number of patients with osteoporosis in the next 2 decades, associated not only to personal complications to each individual affected by the pathology, but also with an important financial burden for healthcare systems [1].

Vertebral compression fractures (VCFs) are common in older patients suffering from osteopenia or osteoporosis and can cause mild to severe back pain, which can have an important impact in the patients' daily life, as far as it can affect their ability to perform the everyday activities and can be associated with several complications [2, 3]. Most of these fractures are stable, i.e., can't be dislocated by physiological forces or movements and, in these situations, the treatment is conservative (bedrest, pain control and surveillance), with no need for surgical intervention [3].

In situations where there is persistent pain or neurological deficits which compromise the ability for daily living activities and shorten the healthy life expectancy the surgical intervention becomes crucial. As the patients are usually older, the physician must take in

account their comorbidities and the possibility of perioperative complications associated with these invasive procedures [4]. Another challenge related with surgical intervention in an osteoporotic vertebral column is directly related to the decreased bone quality, which may worsen the outcome of the intervention and increase the risk of postoperative complications [5].

In this context, it is very important to do further investigation on the degenerative vertebral column, allowing better knowledge on the consequences of compressive forces in the osteoporotic spine and clarifying some challenges related with surgical treatment e in these patients. Thereby, more scientific evidence on this topic can be produced, supporting the physician decision when dealing with osteoporosis treatment.

1.2 Objectives

The present dissertation has the purpose of researching the impact of increase stress concentration on an osteoporotic vertebral spine and its correlation with increased risk of vertebral compression fractures in patients with osteoporosis especially in elderly people.

In order to accomplish the goal, first the biomechanical behaviour of a vertebral column must be recreated into a three-dimensional model, then a mesh must be implemented and three different loading conditions are applied to the relevant structures modelled and finally numerical studies are conducted based on the finite element method.

For the purpose of the present work, a normal and healthy dorsolumbar segment of the spine (T11 to L3) is compared with an osteoporotic one.

1.3 Structure

The present document is divided into six chapters

The second chapter covers all the literature review necessary for an in-depth knowledge of the vertebral column's anatomy and function.

The chapter 3 introduces the basic principles of spinal biomechanics and a general approach on vertebral column pathology, with a special incidence on osteoporosis and spine degeneration.

The chapter 4 allows an overview on finite element modulation of the vertebral column and explains the boundary conditions, the loads applied and the differences on mechanical properties between the two presented models (healthy *versus* osteoporotic).

Chapter 5 presents the results obtained and further discussion on the comparison between the response of a healthy and osteoporotic vertebral column when exposed to load bearing.

Finally, chapter 6 summarises the main conclusions of the work developed and presents suggestions of future works interesting in this context.

Chapter 2

Anatomy of the Vertebral Column – Literature Review

The vertebral column is a central axis responsible for weight-bearing, movement and protection of the spinal cord. The present chapter will describe in detail the human vertebral spine anatomy and functionality.

2.1 Definition

The vertebral column is a strong central axis that presents as a linkage of individual bones called vertebrae and, along with 12 pairs of ribs and the sternum, forms the skeleton of the trunk. The adult vertebral column consists of 33 vertebrae separated from each other by fibrocartilaginous intervertebral discs, except for the first two cervical vertebrae. Superiorly, the vertebral column articulates with the skull, providing the essential support for this structure and, inferiorly, with the two hip bones, which articulate between each other to form the pelvic girdle [6, 7].

In a cephalocaudal sequence, the vertebral column is divided in five regions: cervical (seven vertebrae), thoracic (twelve vertebrae), lumbar (five vertebrae), sacral (five fused vertebrae) and coccygeal (four fused vertebrae), as seen in figure 1. The cervical, thoracic and lumbar vertebrae are moveable. On the other hand, the sacrum and coccyx are formed by the fusion of five and four immoveable vertebrae, respectively [6, 7].

The vertebral column has different curvatures in the adult. The cervical lordosis (convex forwards) develops when a baby starts supporting the weight of the head and has its apex between C4 and C5. The thoracic kyphosis (convex dorsally), which develops during fetal development, presents its apex between T6 and T9 and can be exaggerated in the elderly due to bad posture or osteoporosis. The lumbar lordosis, that develops when the child starts standing

and has/supporting body weight and has with its apex in L3. The sacrum and coccyx are anteroinferiorly concave, to form the pelvic curve. The healthy column has well-marked curvatures in the sagittal plane and no significant lateral curves. Those may happen in a deformity called scoliosis, with possible neural compression and or herniation [6, 8].

The vertebral column's morphology is influenced by mechanical, environmental and genetic factors, which affect its reaction to dynamic forces of the everyday life, namely compression, traction and shear, which vary in magnitude and are influenced by occupation, locomotion and posture [6].

There are three main factors which provide stability and flexibility to the vertebral column: the intervertebral discs, reinforced by anterior and posterior ligaments, the facet joints and the vertebral arches ligaments. These structures will be better described and analysed further in this chapter [7].

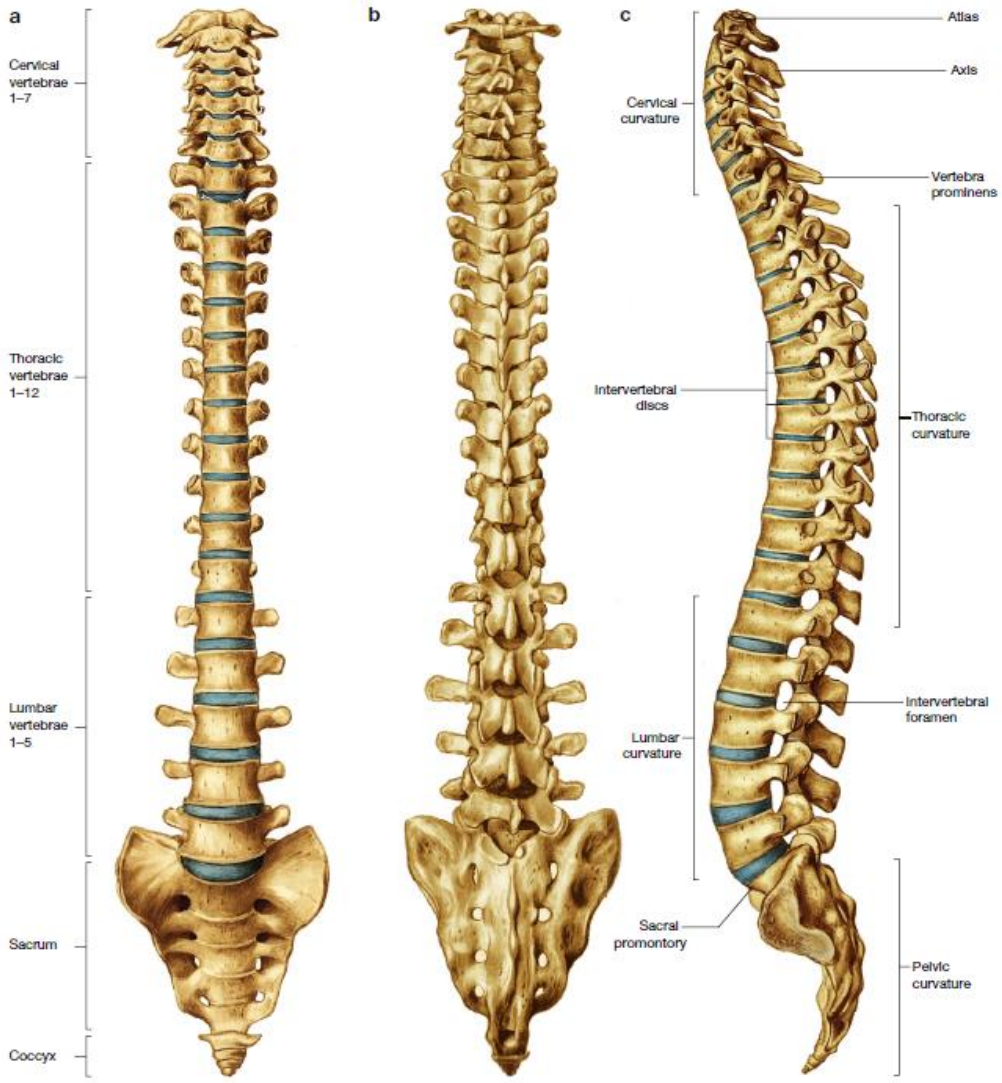

Figure 1 - The vertebral Column [6]

2.2 Structure

The spinal column is a complex structure composed of bone, cartilage, ligaments and sustained by muscles. This subchapter describes in detail the anatomy of the vertebral column.

2.2.1 The Vertebrae

A typical vertebra includes a ventral body, a dorsal vertebral arch with processes and a vertebral foramen, where the spinal cord, meninges and vessels can be found. The adjacent bodies are bound by discs of fibrocartilage in one strong but flexible axis. Near the junctions between the neural arches and the vertebral bodies there are intervertebral foramina that transmit spinal nerves, small recurrent nerves, blood and lymphatic vessels [6].

The vertebral body shape, size and proportion is different according to the area of the column where they are located. For example, in the anterior view, there is a cephalocaudal increase in the vertebral body size from the second cervical vertebra to the third lumbar vertebra, associated to the increase load-bearing function in this area. On the other hand, there is a significant decrease on the vertebral size of vertebrae through the sacrum until the coccygeal apex [6].

The vertebral arch presents in its ventral area a short and thick structure called pedicle and dorsally a successively broader lamina. It also presents pared transverse, superior and inferior articular processes projecting from its junctions and a dorsal spinous process projecting from the junction of the lamina, as seen in figure 2 [6].

Internally, the vertebra consists in trabecular bone that contains red bone marrow, covered by an outer layer of compact bone, that thickens in the arch and process areas [6].

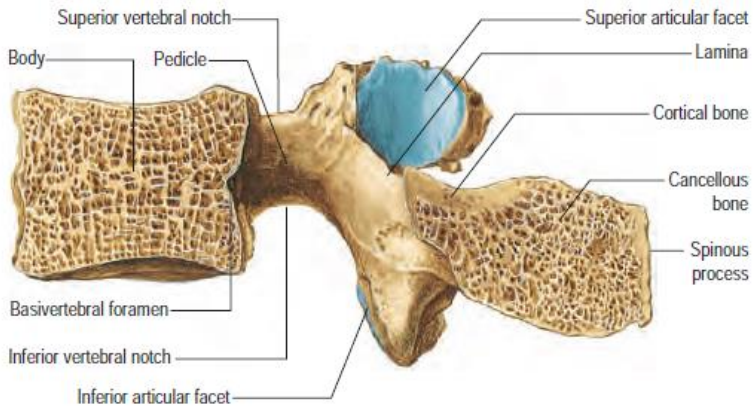

Figure 2 - Parts of a lumbar vertebra (median sagittal section) [6]

2.2.1.1 Cervical vertebrae

The cervical vertebrae are small moveable vertebrae. A typical cervical vertebra presents a small broad body, two pedicles that project posterolaterally and a longer lamina that projects posteromedially, forming a large triangular foramen. It also presents two transverse processes with a foramen in which one of them, that transmits the vertebral vases and nerve. The laminae join the pedicles laterally and a short and bifid spinous process posteriorly [6].

There are three cervical vertebrae with special features:

- Atlas (C1), the first cervical vertebra, which consists of two masses connected by two arches, so it doesn't incorporate a vertebral body. It articulates superiorly with the occipital bone supporting it and allowing flexion-extension movements;
- Axis (C2), the second cervical vertebra, presents an odontoid process (dens), which projects superiorly from its body to articulate with atlas, allowing rotation of the head and atlas around the dens;
- Vertebra *prominens* (C7), the seventh cervical vertebra, presents a non-bifid long spinous process which ends in one tubercle where the ligamentum nuchae and several dorsal muscles attach [6].

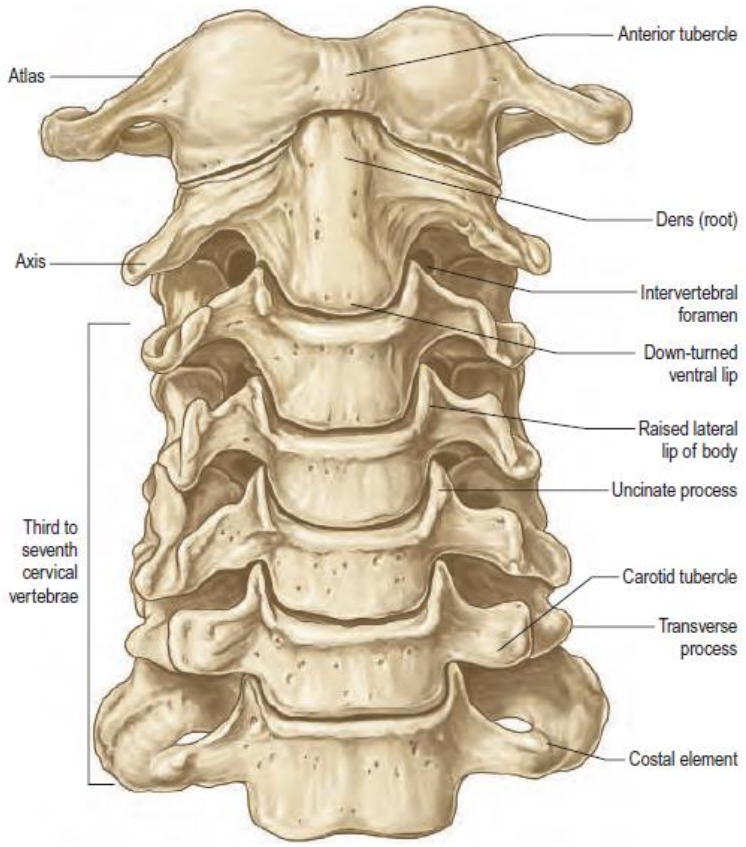

Figure 3 - Anterior view of the cervical vertebrae [6]

2.2.1.2 Thoracic Vertebrae

The twelve thoracic vertebrae present a cylindric body, a small circular vertebral foramen, short, broad and thick laminae and a spinous process that projects downwards. One important characteristic of these vertebrae is that they display lateral costal facets which articulate with the ribs' head and tubercle.

The thoracic column is a transition area, so the bodies of the superior vertebrae progressively change from cervical to thoracic characteristics and the lower ones from thoracic to lumber type. The fifth to eight thoracic vertebrae present a flattened left side for the pressure exerted by the thoracic aorta [6].

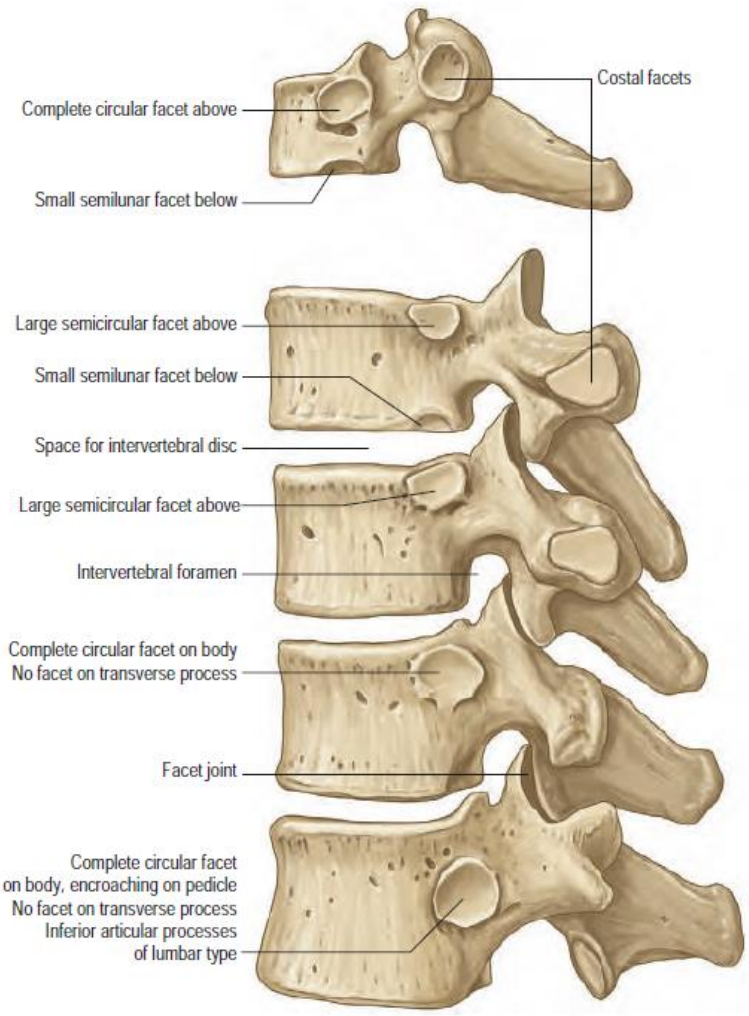

Figure 4 - T1, T9, T10, T11 e T12 (lateral view) [6]

2.2.1.3 Lumbar Vertebrae

The lumbar column presents the largest moveable vertebrae, that differentiate from the other vertebrae by the absence of transverse foramina and costal facets. They present a large triangular vertebral foramen, short pedicles and a quadrangular spinous process with thick posterior and inferior borders. They also exhibit rough mammillary processes in the posterior borders of the superior articular processes. Their transverse processes are long and thin, with small accessory processes in their roots. There is a mammillo-accessory ligament unifying the mammillary and accessory processes, which can be ossified in some people. This ligament protects the medial branch of the dorsal primary ramus of the spinal nerve [6].

The lumbar vertebrae present reciprocally concave and convex articular facets and intervertebral discs between them, allowing a larger mobility with flexion/extension, lateral bending and rotation [6, 9].

The five lumbar vertebrae are large and durable, allowing the dispersion of superior axial forces (from the head, neck and trunk) and protecting the spinal cord. The adult spinal cord generally ends at the middle third of L1, so the first lumbar vertebral foramen contains the conus medullaris. Below this level, there is the cauda equina, a set of spinal nerve roots. This way, the lumbar column permits a two-way communication between the central nervous system and the inferior limb. The lumbar lordosis also contributes to transference of the upper body weight to the pelvis, facilitating an efficient bipedal motion [6, 10].

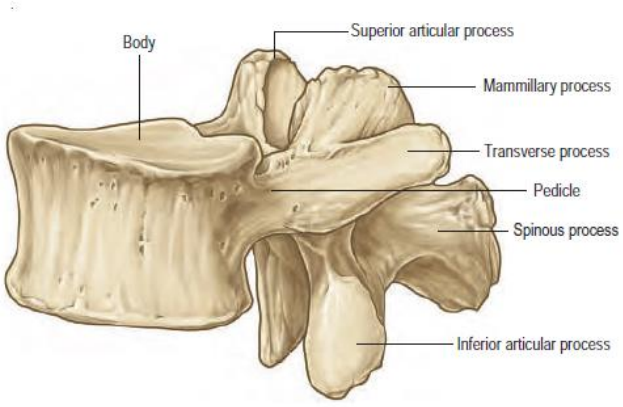

Figure 5 - Lateral view of a typical lumbar vertebra [6]

2.2.1.4 Sacrum

The sacrum is large and triangular, resulting from the fusion of five sacral vertebrae. It articulates laterally with the two hip bones (at the sacroiliac joints), consisting in the posterosuperior limit of the pelvic cavity. Its wide base articulates superiorly with L5. The body of the first sacral vertebra projects anteriorly to form the sacral promontory [6].

In the pelvic surface of the sacrum there are four pairs of anterior sacral foramina which communicate with the sacral canal through the intervertebral foramina. In the dorsal surface of the sacrum there is a median sacral crest, which results from the fusion of the four superior sacral spines [6].

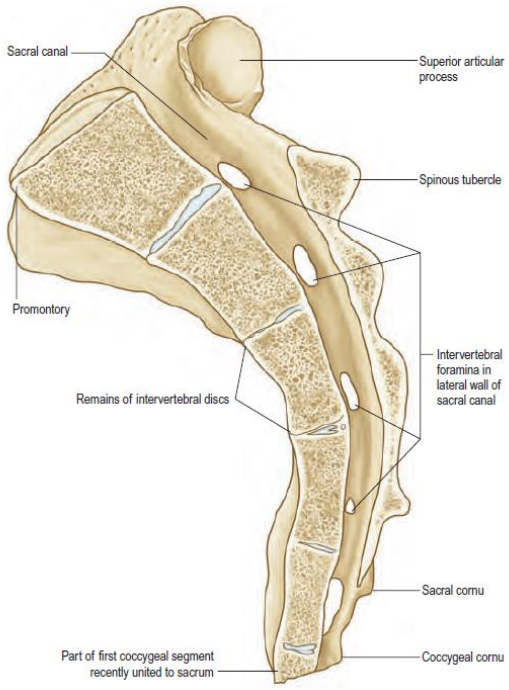

Figure 6 - Lateral aspect of the sacrum [6]

2.2.1.5 Coccyx

The coccyx, or tailbone, is found at the end of the vertebral column, projecting downwards from the sacral apex. It consists in four small fused vertebrae, as seen in figure 7, and articulates with the sacrum in the sacrococcygeal joint, which includes a fibrocartilaginous

disc and two zygapophysial joints. The sacrococcygeal joint allows limited anterior flexion while weight-bearing in the sitting position [6, 11].

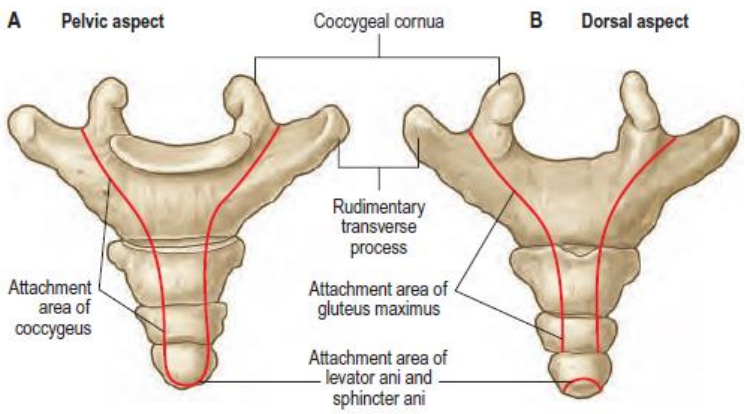

Figure 7 - Coccyx (A - anterior aspect; B - posterior aspect) [6]

2.2.2 Joints

Vertebrae from C2 to S1 articulate between them through secondary cartilaginous joints (symphyses or intervertebral discs), synovial joints between the articular processes and fibrous joints between the laminae, transverse and spinous processes [6].

2.2.2.1 The Vertebral Joints (Intervertebral Discs)

Between two adjacent vertebrae, there is an intervertebral disc, a cartilaginous structure which includes an annulus fibrosus, a fibrous ring capable of withstand torsional and shear stresses, and a nucleus pulposus, a gelatinous gel with compressibility. Through the column there are 23 intervertebral disc – the first on located between C2 and C3 and the last one located at the lumbosacral articulation – and they consist in 25% of the column's length. Between the vertebral body and the disc there is the endplate, made up of hyalin cartilage [6-8].

These structures work as shock absorbers, being extremely important in load-bearing and relaxing, and support the anterior and longitudinal ligaments, contributing, in simultaneous, for the stability and flexibility of vertebral column [8].

The intervertebral discs are thin in the superior thoracic column and thicker in the lumbar column. In this region, they tend to be thick in its anterior part, contributing to the lumbar lordosis [6, 7].

2.2.2.2 The Zygapophyseal Joints

The facet or zygapophysial joints are typical synovial articulations between the articular processes of the vertebrae. The size and shape of the articular facets is different depending on the region of the vertebral column and the type of movement that takes place in that area [6, 7].

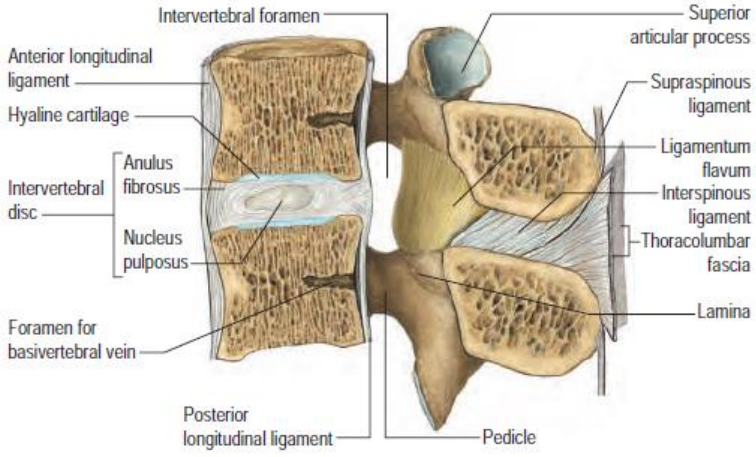

Figure 8 - The intervertebral disc and the ligaments [6]

2.2.3 Ligaments

The ligaments of the vertebral column contribute to its stability and are extremely important in the adjusting of the different phases of its movements. There are ligaments of the vertebral bodies and intervertebral discs and ligaments of the vertebral arches. The laxity of ligaments may lead to instability of the column, especially in trauma situations [6, 12].

2.2.3.1 Anterior Longitudinal Ligament

This ligament is a strong band that extends along the anterior surfaces of vertebral bodies, from the basilar part of the occipital bone to the upper portion of the sacrum. It is thicker

and narrower in the thoracic column and broader at the end of the column. The fibres of the ligament are strongly attached to the intervertebral discs, the endplates and the margins of the vertebrae. This ligament limits the extension of the column, preventing its hyperextension [6, 12].

2.2.3.2 Posterior Longitudinal Ligament

This ligament lies in the vertebral canal, along the vertebral bodies' posterior surface, from C2 to the sacrum. At the cervical and superior thoracic column it is broad and uniform and at the inferior thoracic and lumbar column it is denticulated (narrow over the bodies and broad over the discs). The oblique orientation of its fibres permits a slow rise in tension in the final stages of the principal movements of the column. This ligament also prevents hyperflexion of the column [6, 12].

2.2.3.3 Ligament *Flavum*

This is a highly elastic ligament which connects the laminae of adjacent vertebrae inside the vertebral canal. It is thinner and broader in the cervical column and thicker at lumbar level. It prevents abrupt limitation of spinal flexion and assists restoration of the erect position of the column after flexion, protecting the intervertebral discs from injury during the movement [6].

2.2.3.4 Interspinous Ligament

These ligaments connect adjacent spinous processes, presenting as narrow elongated structures in the thoracic column and thick quadrilateral ligaments in the lumbar column. In this region, the ligaments connect with thoracolumbar fascia and joint capsules [6, 12].

2.2.3.5 Supraspinous Ligament

This ligament is a strong and fibrous cord, composed of elastic collagenous fibres, which connects the spinous processes from C7 to L3/L4. Below this last vertebra, it is replaced by fibres of the muscle *latissimus dorsi*. It only presents as a separated structure in thoracic and

upper lumbar column. It exerts mechanical forces at the end of the ventral flexion, complementing the action of the ligament flavum [6, 12].

2.2.3.6 Intertransverse Ligament

These ligaments connect adjacent transverse processes, presenting different anatomy according to the column area where they insert [6].

2.2.3.7 Capsular Ligament

This ligament encloses the facet articulating joints of the vertebral column, conferring a particular important stability to the column, especially during its extension (along with the anterior longitudinal ligament) and its lateral bending [13].

2.2.4 Muscles

The muscles of the back are crucial in maintaining posture and distribution the forces exert on the vertebral column by the weight of the body. They are arranged in layers, being the deeper one formed by intrinsic back muscles, which lie below the thoracolumbar fascia and are innerved by branches of the dorsal rami of spinal nerves. The intrinsic muscles are organised in three different layers [6]:

- The superficial layers include the splenius capitis and cervicis (in the neck/upper thorax), responsible for the neck extension, flexion and rotation, and the erector of the spinae muscles (in the trunk), responsible for the extension and stabilization of the column [6-8];
- The deep layers include spinotransverse group - which includes the semispinalis, *multifidus* and *rotatores* - the suboccipital muscles, and interspinal and intertransverse muscles (deeper in this layer);
- The latter group is formed by dorsal and ventral spinal muscles.

The superficial layer is composed by extrinsic muscles, innervated by *ventral rami*. This layer divides in two more groups of muscles:

- The superficial layer, formed by muscles that run from de upper limb to the axial skeleton and control the limbs' movements, including trapezius, latissimus dorsi, elevator scapulae and rhomboid muscles [6];
- The intermediate layer includes the serratus posterior group of muscles. They are responsible for the respiration, as they are involved in the rib movements, and (possibly) proprioceptive functions [6, 8].

The suboccipital muscles are found in the back of the neck and responsible for the head movements. They include the rectus capitis posterior major, obliquus capitis superior, and obliquus capitis inferior, which form the suboccipital triangle [8].

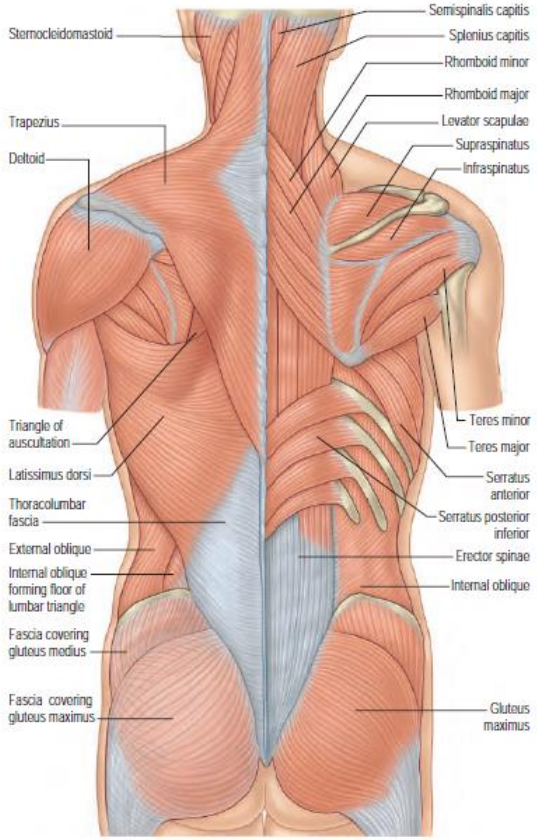

Figure 9 - Superficial muscles of the neck and trunk [6]

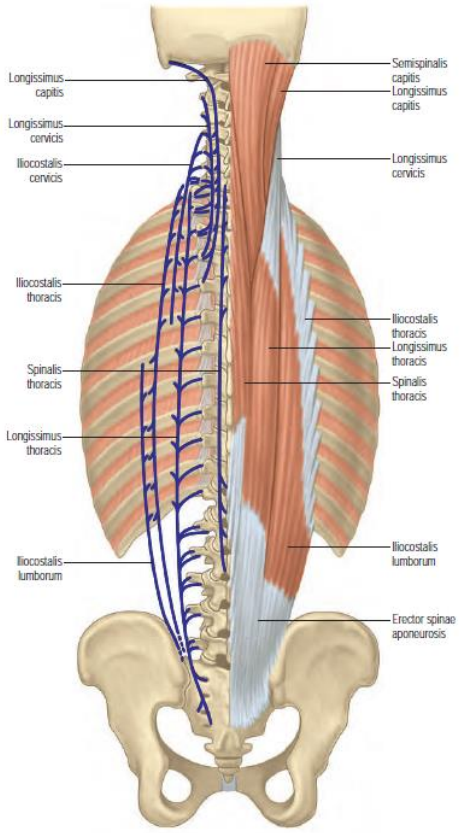

Figure 10 - The erector of the spine [6]

2.3 Functions of the Vertebral Column

The vertebral column presents crucial functions, namely [6, 8]:

- To support the head and to transfer the weight from the head and trunk to the abdomen and legs;
- Along with powerful muscles that are attached to its posterior part, to provide the structure necessary to maintain the posture of each individual and the flexibility necessary to maintain the movement of the upper body, allowing rotation and bending;
- To protect the spinal cord, nerve roots and vasculature that runs through the vertebral canal from external trauma;
- To contribute to the haemopoiesis throughout lifetime.

Chapter 3

Spinal Biomechanics

3.1 Vertebral Spine as a Functional Unit

As previously stated, the vertebral column is a vertical axel which presents with three main biomechanical functions: to ensure the load transfer from the trunk and superior limbs maintaining the spine stability; to allow its mobility and flexibility and to safeguard the spinal cord from injuring forces or movements. The lumbar spine is the most vulnerable part of the vertebral column as it simultaneously supports the most significant loads and presents the maximal mobility [14].

The biomechanical assessment of the vertebral spine includes the assessment of movements and forces acting on the spine and are its direction is described in relation to a three-dimensional cartesian coordinate system of the body, being its centre located at the base of the column. This system is presented in figure 11 [14]

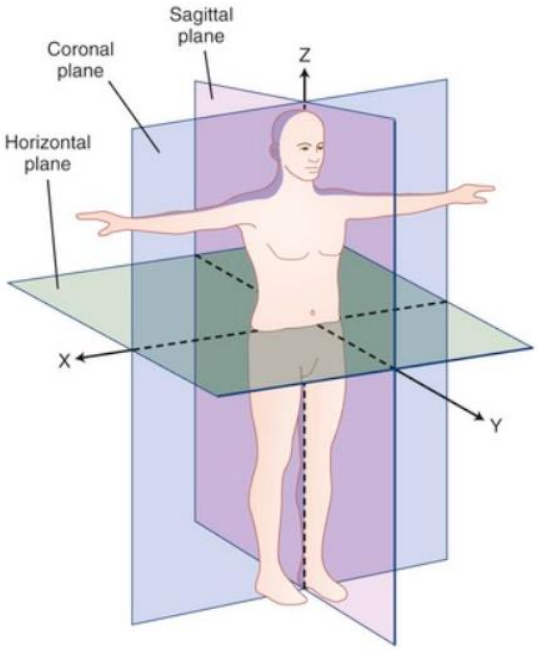

Figure 11 - Anatomy view plans of the human body [14]

3.2 Loads acting on the Lumbar Column

There are two types of loads acting on the vertebral column, the physiological (such as flexing/extension, sitting/standing, gait and walk) and traumatic ones (as impact or whiplash). The body is also subjected to the gravity load, proportionally to the body mass and which can be multiplied in acceleration, fall, acceleration/deceleration situations [15].

The main internal force that acts on the lumbar column a compressive force which acts perpendicularly to the middle plane of the intervertebral discs, causing its compression. There also exist sagittal and lateral shear forces, which act in the middle plane of the discs, causing their slope to each other [15].

The components causing the flexion/extension and lateral bending of the vertebral column are the sagittal and the coronal planes, respectively. On the other hand, the moment component causing the rotation of the spine about its long axis is called a torsional moment, and it is described on the transverse plane [14, 15].

The tensile force acts perpendicularly to the middle plane of the intervertebral discs causing its elongation. There is no pure tensile force acting on the vertebral column, but some therapies resort to this kind of tension [15].

3.3 Spinal Disorders

The vertebral column may be affected by several medical conditions, such as [8]:

- Osteoarthritis, the most common type of arthritis, frequent in the elderly and characterized by a progressive erosion of the joint cartilage;
- Osteoporosis, a common disease among women aged over 65 years and a condition which increases the risk of a vertebral compression fracture;
- Spinal disc herniation, when discs tear at its periphery facilitating the herniation of its nucleus, causing pain, weakness, numbness or even decreased reflexes;
- Spinal cord injuries, in trauma situations, with paraplegia, tetraplegia or other serious complication;

- Spinal stenosis, in context of arthritis, Paget's disease or trauma, which can cause pain, numbness or weakness of the limbs, symptoms that usually improve with anterior bending.

During life, the components of the vertebral column develop degenerative and morphologic changes. Processes as intervertebral chondrosis and osteochondrosis, possibly combined with dislocation or calcification/ossification of the discs, modifications in the vertebral bodies with osteophytosis or arthritic changes of zygapophyseal joint with increased risk of compression of the vertebral artery or narrowing of the intervertebral foramina may occur, causing severe neurologic symptoms and great limitation of the patient's life [16]. Important back pain is frequently present in these patients and often require further a spine MRI [17].

On the other hand, spinal trauma can take place in situations of vehicle accidents, falls, violent conflicts or sports. These situations may be associated with spinal cord injuries and often related to high morbidity and mortality [18]. Almost 90% of spinal lesions involve the thoracolumbar column and 50% of these injuries occur between T11 and L1 [19].

As the present work will focus on the degenerative column, its particularities and consequent damages, the following subchapters will describe in more detail the most interesting pathologies in this context.

3.3.1 Osteoporosis and Intervertebral Disc Degeneration

As referred above, osteoporosis is a skeletal pathology characterized by a decrease in the quality and strength of the bone, caused by a diminished trabecular bone volume, with an increased risk of bone fractures. There are several risk factors for osteoporosis, namely the body mineral density (which decline over the 4^{th} decade), the bone turnover and microarchitecture, the skeletal geometry and muscle [20]. A low body mass index is another important risk factor, as observed in figure 14 [21].

This condition is particularly relevant in the elderly and female population, which is why assessment of fracture risk is recommended in woman aged 65 years and over and men aged 75 years and over. There are multiple clinical risk factors for bone fracture, such as former fragility fracture, glucocorticoid treatment, parental history of hip fracture, current smoking and excessive alcohol intake, as presented in figure 12 [22]. There also exist secondary causes of osteoporosis which must be considered, such as the diseases listed in figure 13 [20].

Previous fragility fracture[a]
Oral or systemic glucocorticoids[a]
Untreated early menopause (or male hypogonadism)[a]
History of falls[b]
Family history of hip fracture[b]
Secondary osteoporosis[b]
Low BMI (<18.5 kg/m^2)[b]
Smoking[b]
Alcohol intake[b] Women: >14 units/week Men: 21 units units/week

Figure 12 - Clinical risk factors for women aged 65 years and over and men aged 75 years [22]

Endocrine Early menopause Hyperthyroidism Hyperparathyroidism Hyperprolactinaemia Cushing's disease Diabetes mellitus
Gastrointestinal Coeliac disease Inflammatory bowel disease Malabsorption syndromes e.g. short bowel
Rheumatological Rheumatoid arthritis
Haematological Multiple myeloma Haemoglobinopathies Mastocytosis
Respiratory Cystic fibrosis Chronic obstructive lung disease
Metabolic Homocystinuria Chronic kidney disease
Immobility For example: neurological injury

Figure 13 - Causes of secondary osteoporosis [20]

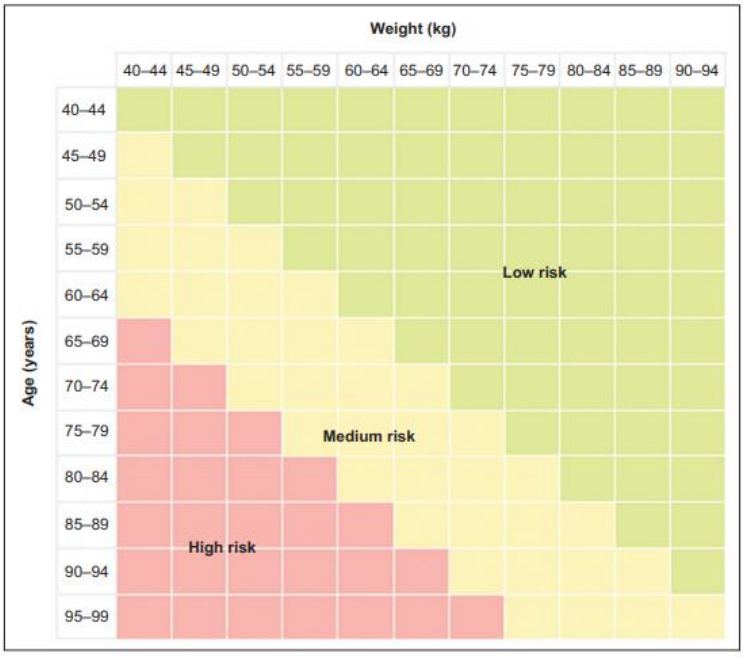

Figure 14 - Diagram showing osteoporosis risk stratification for Singapore women based on the Osteoporosis Screening Tool for Asians [21]

The definitive diagnose of osteoporosis can be obtained through dual-energy X-ray absorptiometry (DEXA) scanning, which evaluates the bone mineral density. When the DEXA BMD T-score is ≤ –2.5, or T-scores between –1 and –2.5 with an associated high fracture risk or in a female with previous fragility bone fracture, treatment such be initiated.

Studies prove that not only is important to detect and prevent low mineral density, but also to prevent the risk of falling and other risk factors for fractures [23]. Being that said, the first line of treatment consists in conservative measures, which include exercises which improve the patients' strength and balance, reducing their falls and consequent fractures, and pharmacological treatment with oestrogen replacement if women under 50 years, menopausal hormone therapy in post-menopausal women between 50 and 59 years specially if symptomatic

and treatment with bisphosphonates, which inhibit bone remodelling, in women over 60 years. The value of administration of calcium and vitamin D remains unclear and needs further investigation. The treatment recommendations are summed in figure 15 [21].

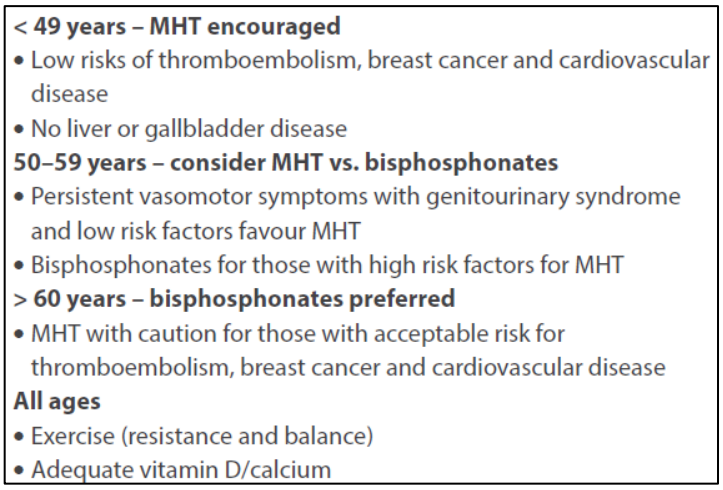

Figure 15 - Menopausal hormonal therapy (MHT) and osteoporosis [21]

It is important to reinforce that intervertebral disc degeneration prevalence also increases with age and it is most common in the lower lumbar column. This degenerative process is particularly pronounced in situations where the column is exposed to excessive mechanical loading, promoting disruption of its structure and a cascade of non-reversible cell-mediated reactions which lead to further disturbance, with consequent pain. There are multiple risk factors to disc degeneration, being the main ones the patient genetic inheritance, aging, nutritional compromise and loading history [24].

The degenerative changes of intervertebral discs and facet joints and ineffective muscle support can lead to destabilization of one or multiple vertebral segments and anterior slipping of the vertebral bodies. This condition, called spondylolisthesis, is more common in the elderly female population and frequently associated to symptoms such as lumbar pain, radicular pain or neurogenic claudication [25]. Some studies also relate aging and intervertebral discs degeneration with structural changes in the vertebral column ligaments, compromising their biomechanical role of maintaining the healthy lumbar spine stability [26].

The vertebrae and the intervertebral discs form a solid unit. Therefore, the health of the bone tissue and the integrity of the attached non-bone tissues are strongly associated. Although studies on the association between osteoporosis and intervertebral discs' degeneration are still inconsistent, it is a fact that these two conditions are the most common degenerative diseases of the spine and that they frequently coexist in older patients. Moreover, scientific evidence demonstrates that osteoporosis may accelerate the degeneration of intervertebral discs, by destruction the integrity of vertebral bodies and endplates, which are fundamental to the preserve discs' function [27].

3.3.2 Spinal Fractures

Spinal fractures are rare in younger people, with their incidence increasing in later years of life because of low bone mass in subjects suffering from osteopenia/osteoporosis [28]. They can also result from trauma situations, especially if these occur in individuals with degenerative diseases of the bone. Patients with vertebral fractures have increased risk of suffering from pain and disability, with an enhanced need to healthcare utilization. The symptoms may be acute or chronic. Most vertebral fractures are diagnosed during investigation of back pain. On the other hand, there is a low rate of vertebral fractures diagnose because of the absence or mild symptoms or e lack of a precipitating event [29].

To facilitate clinical communication and vertebral fracture assessment numerous classification systems were established by experts, which can use several injury characteristics, such as the mechanism of injury, the morphology, anatomic determinants of the fracture stability and neurological status. The AOS classification system includes fracture morphology, neurological status and clinical modifiers, which are relevant in surgical decision making [30].

Vertebral fractures can be classified in three types:

- Type A or compression fractures, which involve the vertebral body and/or intervertebral disc. There are five subtypes:

    - A0 or minor fractures: no fracture or clinically irrelevant fractures of the spinous process or the transverse fracture, which are no concerns to the mechanical stability of column or potential neurological deficits;

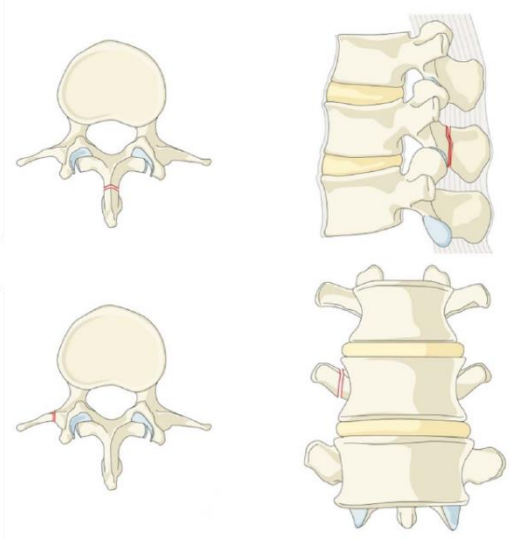

Figure 16 - Subtype A0: Minor injuries [30]

- A1 or wedge-compression/impaction fractures: injurie of a single endplate, with no involvement of the posterior wall;

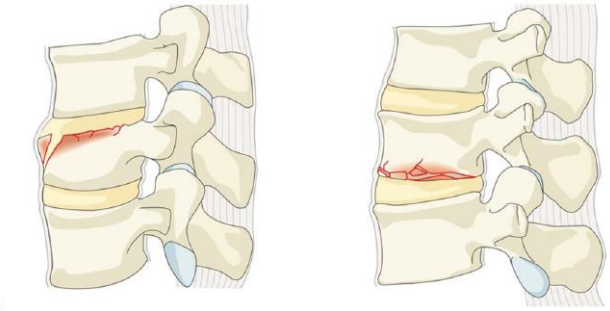

Figure 17 - Subtype A1: Wedge Compression [30]

- A2 or split/pincer-type fractures, which involves both endplates, without involvement of the posterior wall;

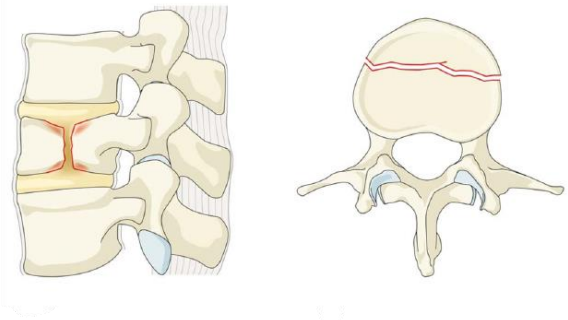

Figure 18 - Subtype A2: Split or pincer-type [30]

- A3 or incomplete burst, an injury affecting a single endplate with involvement of the posterior wall and an exposed vertebral canal. There is preserved integrity of the posterior tension band and, for this reason, no vertebral translation. If injurie of the posterior band is present, the lesion is classified as B2;

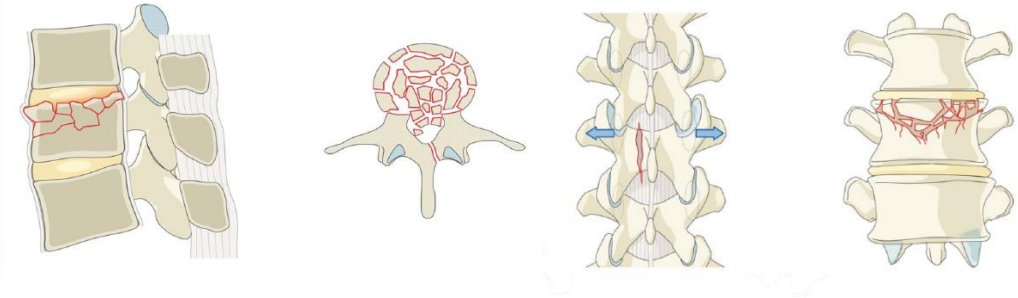

Figure 19 - Subtype A3: Incomplete burst [30]

- A4 or complete burst, a fracture involving both endplates and the posterior wall, without disruption of the posterior band.

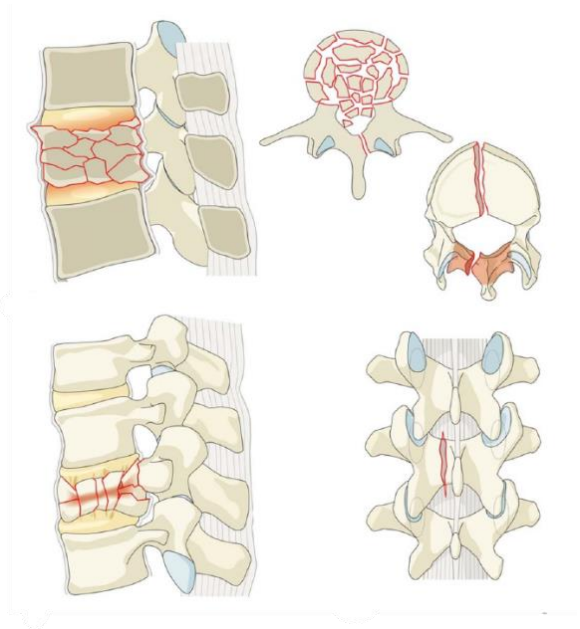

Figure 20 - Subtype A4: Complete burst [30]

- Type B or tension fractures, which result from posterior or anterior tension band failure without potential for gross translation or effective gross translation. These injuries ca be divided in two subtypes:

  - B1 or chance fractures are lesions that include a failure of the posterior tension band and a single vertebral body;

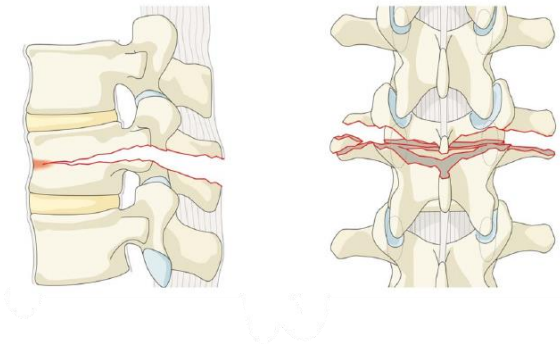

Figure 21 - Subtype B1: Monosegmental bony posterior tension band [30]

- B2 fractures include a posterior tension band lesion and affects an intervertebral level. It can have osseous involvement or not;

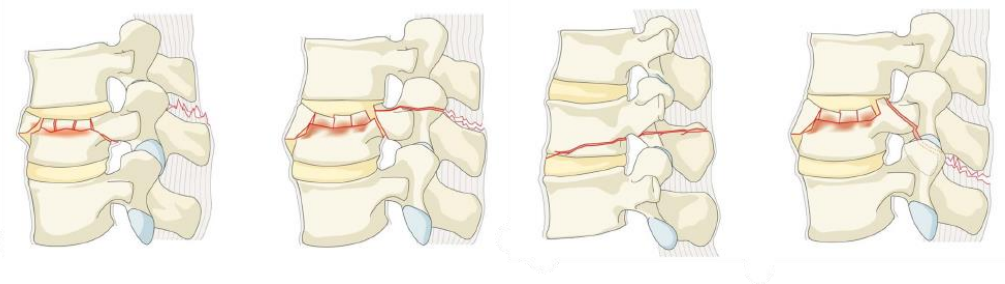

Figure 22 - Subtype B2: Posterior tension band disruption [30]

- B3 or hyperextension injuries consist in disruption of the anterior band, resulting in hyperextension of the column, with intervertebral or interosseous lesion.

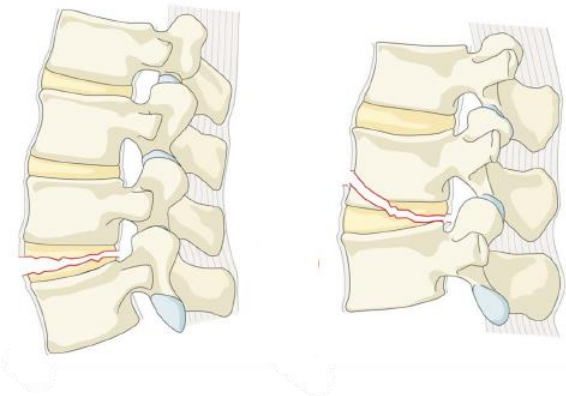

Figure 23 - Subtype B3: Hyperextension injury [30]

- Type C or displacement/dislocation fractures take place when there is displacement dissociation of cranial and caudal segments of the column, which can present in various forms.

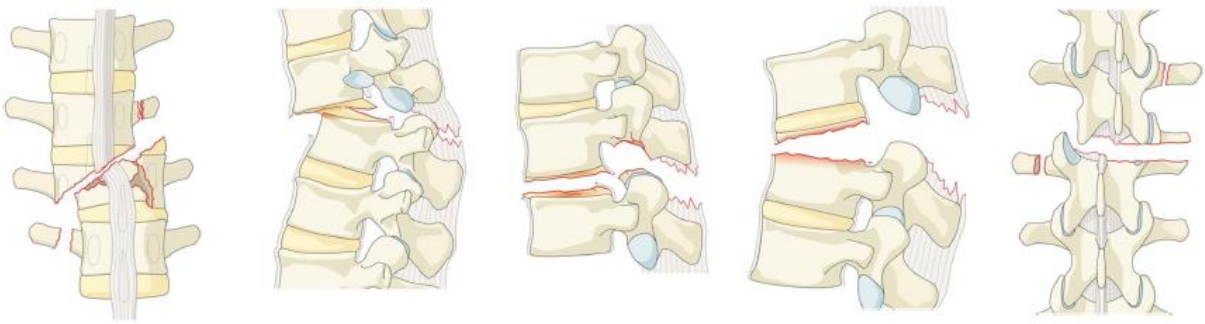

Figure 24 - Images of thoracolumbar C-type injuries [30]

It is important to enhance that Type A fractures may occur in combination with type B or type C injuries. A and B1 injuries affect a single vertebral level while B2, B3 and type C injuries affect a motion segment.

In the patient with osteoporosis there is an increased risk for vertebral fractures, most of them of the compression type, probably due to stress distribution changes of the vertebral body, which consists in the main focus of the present study [31, 32]. In these situations, there are different treatment options that must be considered: conservative treatment (if the fracture is non-displaced, with minimal pain and no neurological deficits), conventional surgery, or minimally invasive techniques such as cementoplasty or percutaneous instrumentation, when there are important symptoms and radiological alterations. There is a particular challenge when surgical intervention takes place in these cases, as the bone material is diminished, increasing the risk for poor implant hold or postoperative mechanical complications [5].

Chapter 4

Three-Dimensional Finite Element Modelling of the Vertebral Column

This current section will address the techniques implemented to achieve the thoracolumbar spine segment model. As the main purpose of this work is two compare the healthy and osteoporotic vertebral column, there will be shown two models: a healthy column and a severely degenerative column. The osteoporotic model will be created from the first one, by changing the bone properties attributed to the vertebra of the intact model, simulating the loss of bone mass density of a pathological spine.

Finite Element Analysis (FEA) allows the modelling of complex anatomical structures such as the vertebral column and the studying of its structure and biomechanical properties, not only in healthy people, but also in ill people. These models are highly accurate and provide more information on biological structures supressing the need of using animal or cadaveric experiments [33].

In 2021, Ana Rita Reis developed a three-dimensional model of a segment of the dorsolumbar column, from T11 to L3, using CT-scan images of a non-pathological vertebral column [34]. The same model will be used, with the adaptations necessary to serve the objectives of this work.

To better understand the mechanisms that allowed the construction of the model presented by Ana Rita Reis and used as the basis of the present work, the first step was to construct a thoracic vertebra model. The mechanisms and software engaged in this task are better explained in the subchapter bellow.

4.1 Modelling of the Vertebrae

To better understand the modelling work, the first task was to model a vertebra using the 2D medical data from CT (computed tomography) images of a young healthy vertebral column, which were processed in the *Mimics* (Materialise Interactive Medical Image Control System) software, allowing a thoracic vertebra split. Due to the extremal complex vertebral geometry, the key feature on using this software is that *Mimics* relies on CT images which provide a very accurate and precise information on bone geometry which ensures a geometrical precision in the representation of the bone [35].

The process that allows the conversion of anatomical details from 2D CT images to a 3D model is called segmentation [33]. The bone tissue of the vertebra was segmented by thresholding, so the pixels with grey values in the threshold range were worked as bone material and integrated in the segmentation mask. Then, the segmentation mask was converted to a 3D reconstruction using a technique feature in *Mimics* called "Region Growing". After this step, it was important to manually edit the segmentation mask, including pixel by pixel or groups of pixels in the mask, in order to achieve a closer volume. This is a time-consuming procedure, but crucial to obtain an accurate model *[35]*. A smoother shell was obtained through the *Mimics* software function "Smooth".

The file with the smooth 3D shell was exported to the *Materialise 3-matic* software to clean up the imperfections of the model and to create an optimized mesh.

The next step involved the *Abaqus* software, used to create the four-node tetrahedral elements mesh of the solid vertebra. The result achieved is presented in figure 25.

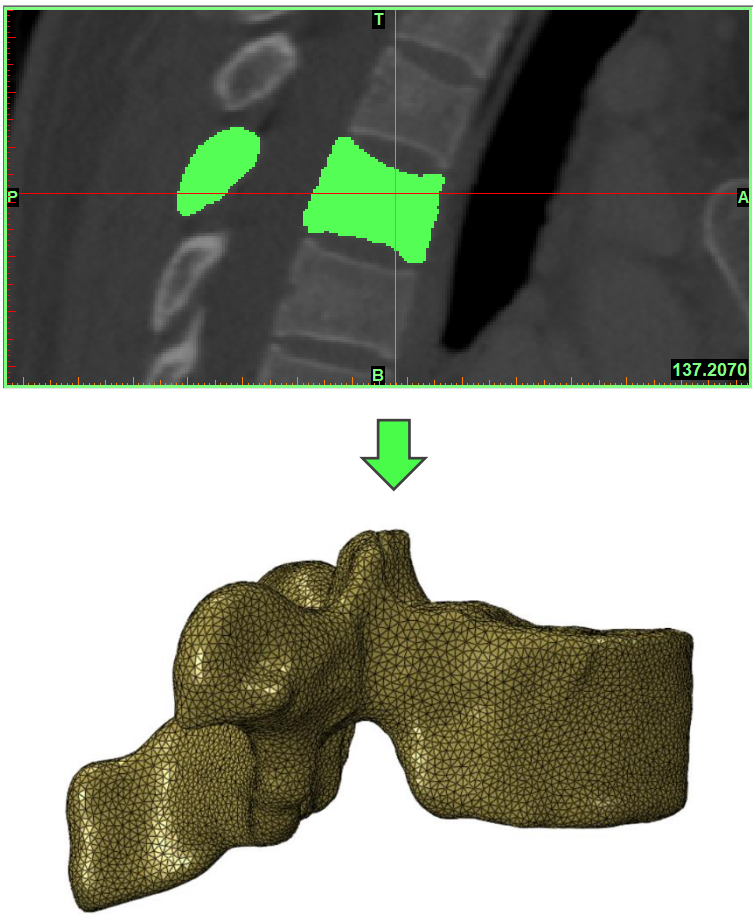

Figure 25 - Modelling process from 2D medical CT scan in sagittal view (upper) to 3D thoracic vertebra model (down)

The files were again imported to the Mimics software to differentiate the bone elements (trabecular or cortical bone) according to the *gray values* of the CT scans. Later, all vertebrae were meshed in *Abaqus* with four-node tetrahedral elements (C3D4).

4.2 Modelling of the Intervertebral Disc and Endplates

A total of four intervertebral discs were recreated via modulation since they were not noticeable in the CT images. The discs were all modulated in the *Rhinoceros 6.0* software.

Since each one of the four-disc modulated are positioned between two consecutive vertebrae, those began to be modelled from two polylines following each vertebral endplate perimeter. By following this method, each outer surface of the annulus fibrosus were made from two vertical curves which united the previous polylines. [34].

To mimic the collagen discs fibres, eight peripheral layers were modelled as can be seen in figure 26 [34, 36].

Between the disc and the surface of the vertebral body, the cartilaginous endplate is located. This endplate covers the nucleus pulposus and some inner fibres of the annulus fibrosus. The three structures of the disc are illustrated in the exploded view in figure 26.

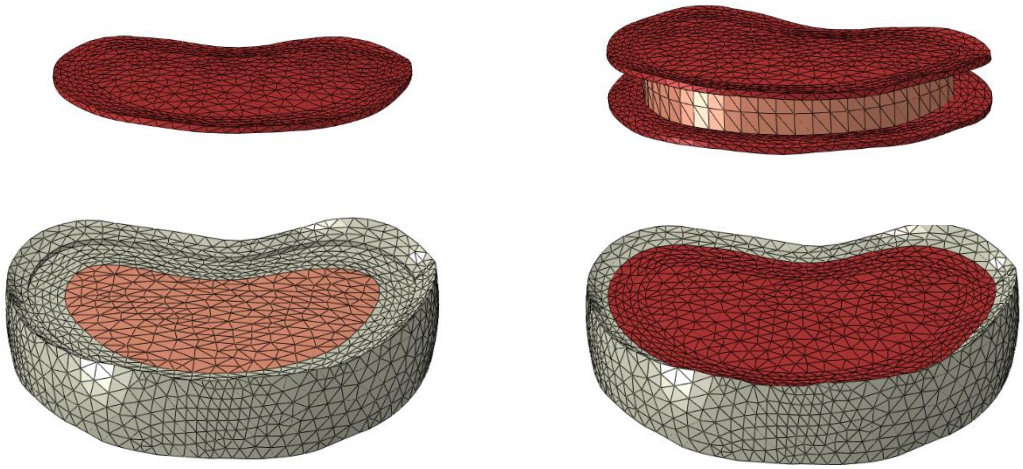

Figure 26 - Structures of an Intervertebral Disc: Endplates, Annulus Fibrosus and Nucleus Pulposus

Each component of the disc was meshed with hybrid 3D tetrahedral elements (C3D4H) [34].

4.3 Modelling of the Ligaments

As presented in chapter 2 subsection 2.2.3, ligaments play a fundamental role in providing stability to the vertebral column. In this thoracolumbar spine functional unit model, seven different ligaments were modelled:

- Anterior Longitudinal Ligament (ALL);
- Posterior Longitudinal Ligament (PLL);
- Ligament Flavum (LF);
- Interspinous Ligament (IL);
- Supraspinous Ligament (SL);
- Intertransverse Ligament (ITL);
- Capsular Ligament (CL).

All ligaments were modelled using the Rhinoceros 6.0 software and were meshed in Abaqus as a two node linear 3D truss element (T3D2) [34].

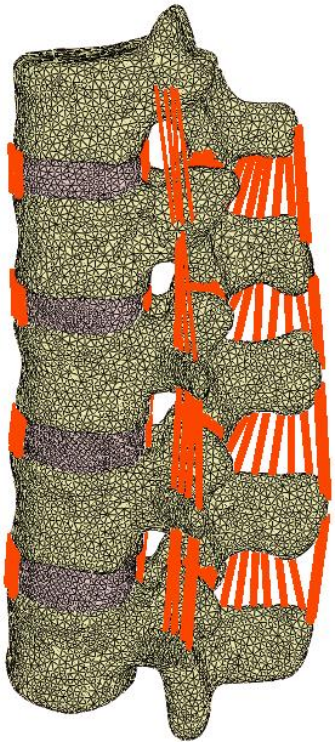

Figure 27 - The spinal ligaments

4.4 Full Functional Model

As stated before, the healthy model of the vertebral column designed by Ana Rita Reis and used as the basis for the present work included vertebrae from T11 to L3, four intervertebral discs and seven types of ligaments involved in this segment and crucial for the vertebral column stability. The complete model is presented in figure 28. The model was previously validated on a bigger scope, since the data obtained were correlated with bibliographic retrieved experimental values available [34].

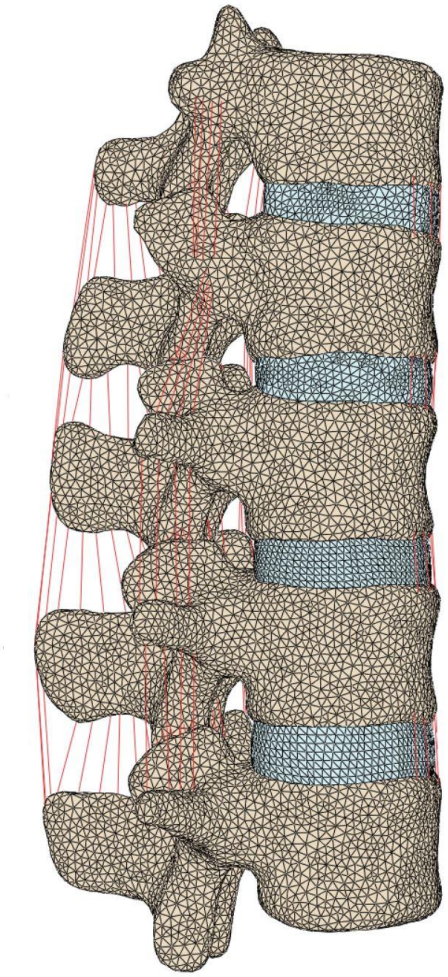

Figure 28 - 3D Model of the thoracolumbar segment

The osteoporosis incidence is higher in the lower thoracic and upper lumbar column, i.e., from T11 to L1 [37]. The advantage of the utilization of the present model is that it includes both type of vertebrae, allowing a more accurate analyses of the disease.

4.5 Loading Conditions Applied in the 3D Model

In order to achieve the finite-elements analysis, three loading situations were applied in the previous model: forward flexion, lateral bending and axial rotation. The only difference was the moment direction. A moment of 50 Nm was applied to the reference point located in the middle of the upper surface of T11 and the impact of the load on the lumbar segment was studied [34].

4.5.1 Boundary Conditions

Bearing in mind that the purpose of the presented model is to simulate a regular vertebral column behaviour when a load is applied, it was necessary to define the adequate boundary conditions. The loads were applied on the T11 superior endplate and the bottom of the model was completely fastened, in order to obtain accurate results. The degrees of freedom at the inferior L3 endplate were restrained in space, as demonstrated in figure 29 [34].

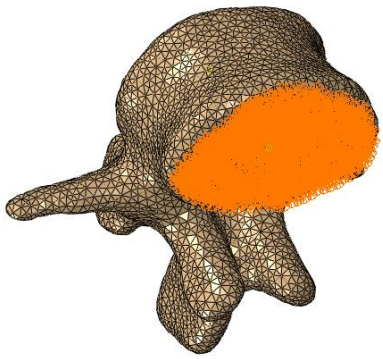

Figure 29 - Boundary condition - L3 inferior endplate fixation

4.5.2 Load Applied

As previously mentioned, a moment of 50 Nm was individually applied to a reference point in each one of the three axis of a standard right-hand Cartesian coordinate system to simulate the three loading modes. The distribution of the load from the reference point trough the endplate nodes is possible with the *Coupling function*, as presented in figure 30 [34].

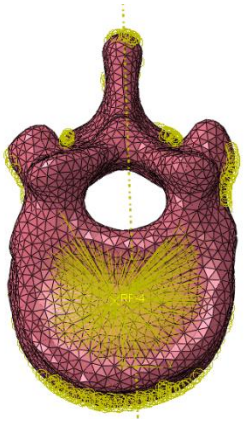

Figure 30 - Demonstration of the coupling function application on Abaqus

4.6 Mechanical Properties

After the modulation of the elements of the vertebral column segment, mechanical properties were attributed to each one of the structures, in order to approximate its behaviour in real life [34]. Therefore, the definition of the material properties of components (such as elastic modulus or Poisson's ratio) is fundamental to allow the finite element analysis [38].

The bone, cartilage and ligaments are elastic materials, being there properties (Young Modulus and Poisson Ration) presented in table 1. The ligaments do not have compression attributes, so they only modify the elastic response of the other materials.

On the other hand, the intervertebral discs behave as hyperelastic material. The *nucleus pulposus* acts as incompressible material and the *annulus fibrosus* as anisotropic material, so the isotropic Neo-Hookean model (with material constants of C_{10} = 0.16 MPa and D = 0.024 [MPa^{-1}], [39]) and the Holzapfel-Gasser-Odgen uniaxial properties (with C_{10} = 0.035 MPa, k_1= 0.296 MPa and D =0.024 [MPa^{-1}], [40]) were the best fit on the definition of their mechanical properties, respectively [15, 34].

Table 1 - Bone, cartilage and ligaments mechanical properties in the healthy model

Elastic component	Properties		References
	Young Modulus (E) [MPa]	Poisson Ratio (υ)	
Cortical bone	12000	0,3	[15, 34]
Trabecular bone	150	0,3	[15]
Cartilage endplate	24	0,4	[34]
ALL	11,9	0,3	[34]
CL	7,7	0,3	[34]
IST	3,4	0,3	[34]
ITL	3,4	0,3	[34]
LF	2,4	0,3	[34]
PLL	12,5	0,3	[34]
SSL	3,4	0,3	[34]

To generate the osteoporotic model, the mechanical properties of the bone were changed, according to the literature available and in order to simulate the bone remodulation typical of the disease. The mechanical properties of cortical and trabecular bone in the degenerative column are presented in table 2. The remaining materials' properties were maintained.

Table 2 - Bone mechanical properties in the osteoporotic model

Elastic component	Properties		References
	Young Modulus (E) [MPa]	Poisson Ratio (υ)	
Cortical bone	5030	0,3	[41]
Trabecular bone	16,5	0,2	[41]

Chapter 5

Results Analysis and Discussion

The results obtained are described and analysed in the present chapter.

The von Mises stress was compared with each component volume. The von Mises stress results for each loading mode are presented in tables 1, 2 and 3. Then, the von Mises stress on each component at each level of the segment were compared between the two models (Healthy versus Osteoporotic). The ratio of the con Mises stress difference is presented in the last column of each table, in percentage, and calculated using the formula below:

$$\frac{Osteoporotic\ column - Healthy\ column}{Healthy\ column}\ x\ 100$$

The Finite-elements analyses was used allowing the comparison of the von Mises stresses on the thoracolumbar segment when different load-modes were applied to the healthy and osteoporotic column.

In the forward flexion situation, the loading of T11 to L3 cortical bones varied between 36.90% and 45.54%, indicating that the von Mises stress increased by these values in the osteoporotic model, as seen in table 3. In the lateral bending load-mode the loading of T11 to L4 cortical bones varied between 22,60 and 39,41%, as demonstrated in table 4. These results also agree with an increase in the stress values in the osteoporotic column. In the axial rotation mode, the increase of stress values in the cortical bone was not observed (table 5). Regarding the trabecular bone, there were no significant differences between the healthy and osteoporotic bone in the three load-modes, as expected.

These results confirm that in the osteoporotic patients the column is subject to greater stress when compared to the healthy column, in the three positions. It also demonstrates that the stress is greater in the cortical bone, which supports the body structure. The results correlate with the conclusions obtained by Kang et al. in 2022 [38].

Table 3 - Von Mises maximum stress results for forward flexion loading mode

Component	Lumbar Level	Healthy Model (MPa)	Osteoporotic Model (MPa)	Loading Ratio (%)
Cortical Bone	T11	68,266	94,707	38,73
	T12	47,108	68,373	45,14
	L1	39,182	57,025	45,54
	L2	49,522	71,475	44,33
	L3	35,484	48,577	36,90
Trabecular Bone	T11	1,874	0,847	-54,80
	T12	1,674	0,796	-52,45
	L1	1,496	0,714	-52,27
	L2	1,403	0,679	-51,60
	L3	1,045	0,442	-57,70

The results were reconstructed in 3D and expressed the differences in von Misses stress distribution of the segment in colour. In figure 33, we can observe that the von Mises stress values are increased in the borders of the surfaces of the vertebrae, adjacent to other structures, in the osteoporotic patients. These higher values are represented in warmer colours. This phenomenon may explain the formation of osteophyte secondary to the column degeneration and the intervertebral disc degeneration, frequently associated to chronic pain in these patients [38]. The cortical component of the bone has an essential role on strength and load support, so its loss, prevalent in elderly and osteoporosis, may explain the higher frequency of bone fractures [42]. The present study demonstrates an inversion in the distribution of stress values on the osteoporotic vertebrae, with an increment of the values in the cortical bone and a reduction in the suffered from the trabecular bone, which once more can explain the increase in prevalence of fractures in this location.

In figures 31 and 32 the von Misses stress values are presented in a way that simplifies the comparison between the healthy and the osteoporotic columns in the three loading modes, with a more expressive difference in the forward flexion situation.

Table 4 - Von Mises maximum stress results for lateral bending loading mode

Component	Lumbar Level	Healthy Model (MPa)	Osteoporotic Model (MPa)	Loading Ratio (%)
Cortical Bone	T11	55,522	68,068	22,60
	T12	65,522	86,169	31,51
	L1	65,303	91,037	39,41
	L2	47,708	63,172	32,41
	L3	38,743	51,790	33,68
Trabecular Bone	T11	1,806	0,748	-58,58
	T12	2,124	0,864	-59,32
	L1	1,937	0,877	-54,72
	L2	2,022	0,865	-57,22
	L3	1,646	0,644	-60,87

Several studies shown an important relation between spinal deformities in patients with osteoporosis and chronic lumbar pain, which could be improved with pharmacological treatment, as previously stated [38]. The present work suggests that the stress changes in the surface of the vertebrae in osteoporotic column may increase the risk of bone fractures in these patients. The incidence of these type of complications could be prevent with proper and timely conservative treatment [43]. The treatment would probably change the physical properties of the column elements analysed and reduce the von Mises stress values demonstrated [38].

Table 5 - Von Mises maximum stress results for axial rotation loading mode

Component	Lumbar Level	Healthy Model (MPa)	Osteoporotic Model (MPa)	Loading Ratio (%)
Cortical Bone	T11	32,614	31,900	-2,19
	T12	46,244	44,665	-3,41
	L1	21,680	20,079	-7,38
	L2	23,557	21,644	-8,12
	L3	35,384	31,178	-11,89
Trabecular Bone	T11	0,168	0,068	-59,52
	T12	0,158	0,062	-60,76
	L1	0,251	0,097	-61,35
	L2	0,184	0,085	-53,80
	L3	0,143	0,049	-65,73

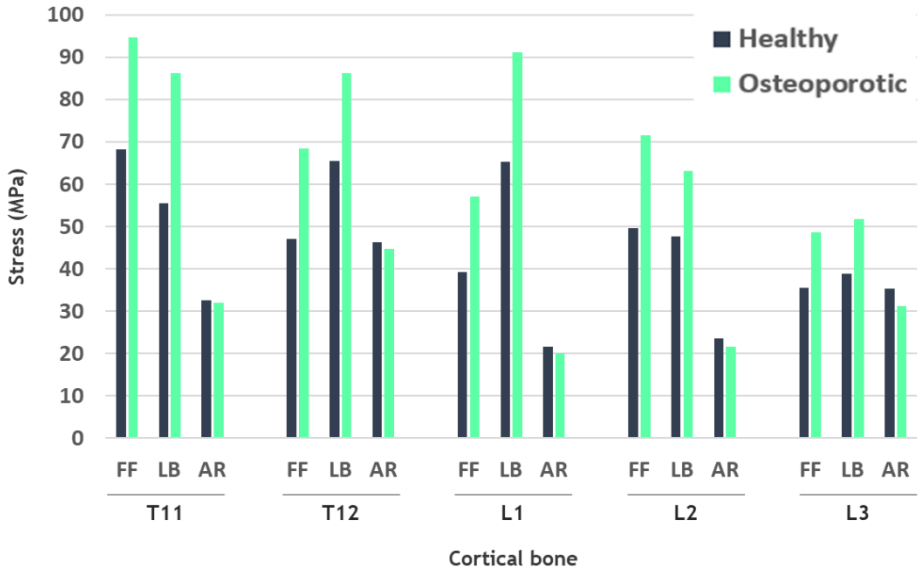

Figure 31 - Von Mises stress results in cortical bone for the 3 loading modes

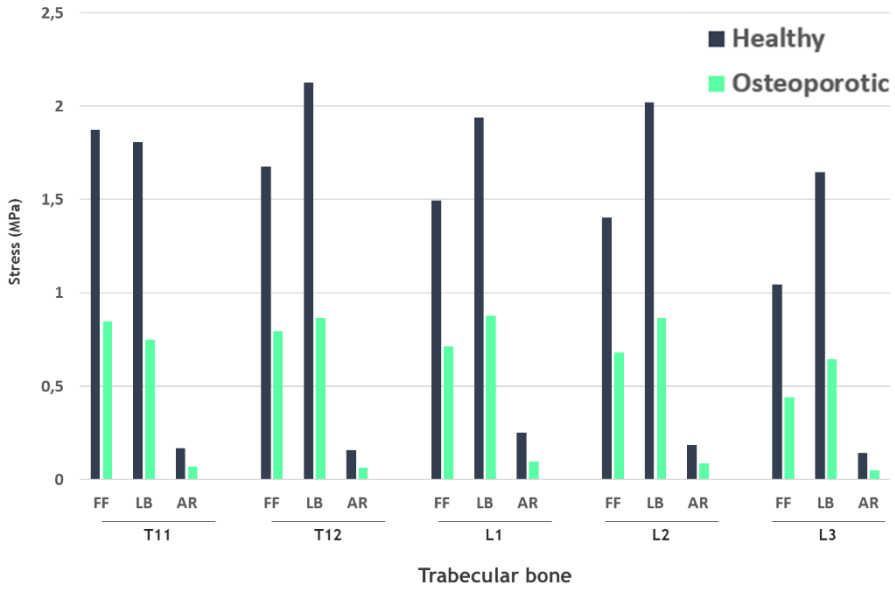

Figure 32 - Von Mises stress results in trabecular bone for the 3 loading modes

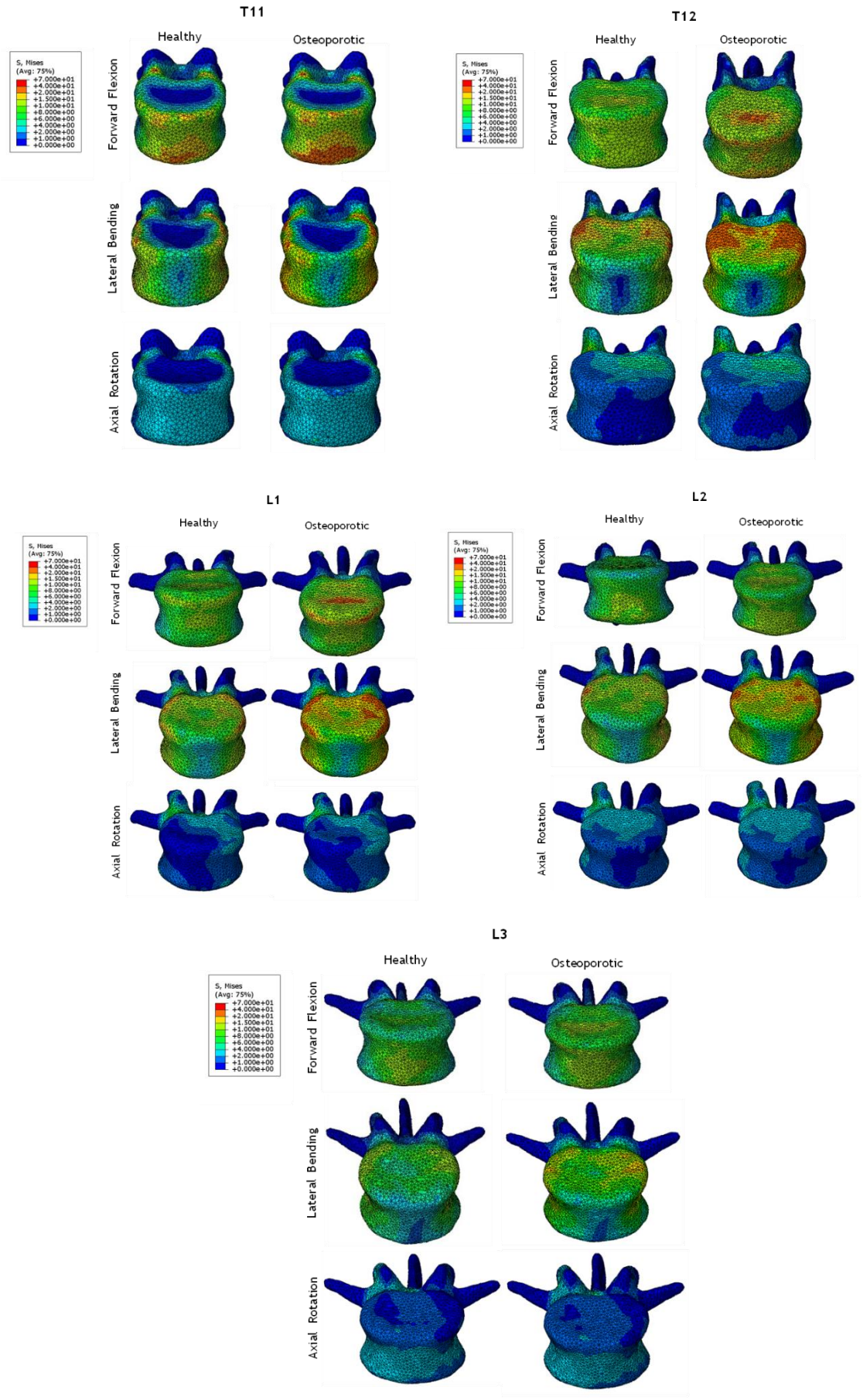

Figure 33 - Stress distribution results at the cortical bone in 3 different motions

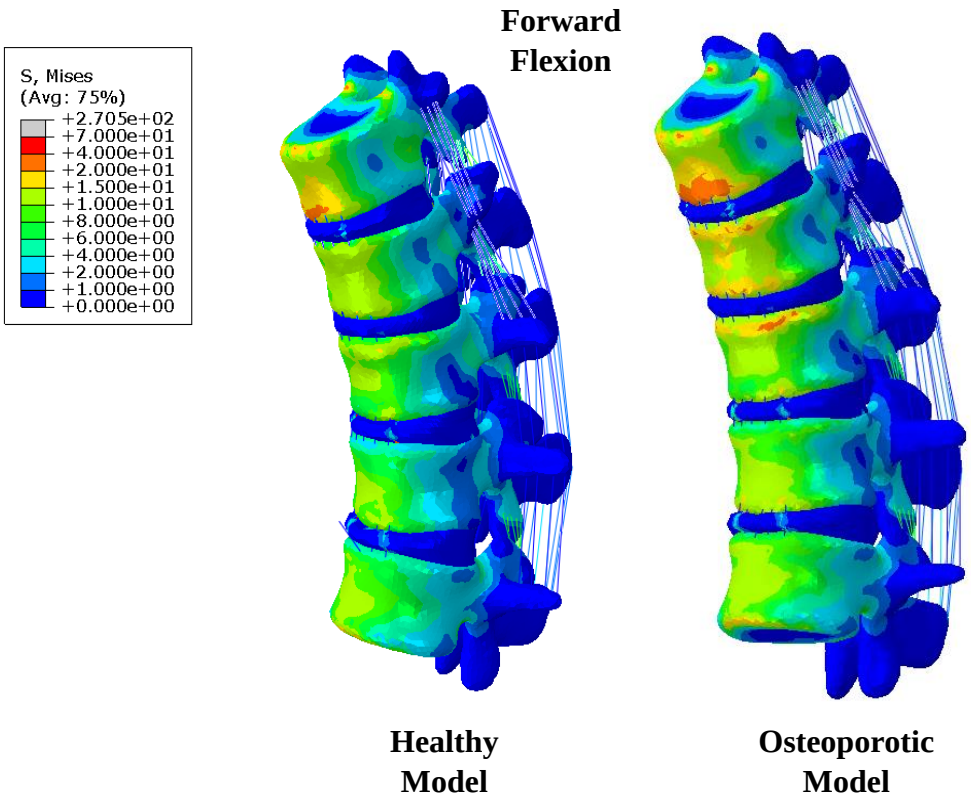

Figure 34 - Von Mises stress distribution of the T11-L3 functional unit for the forward flexion loading mode

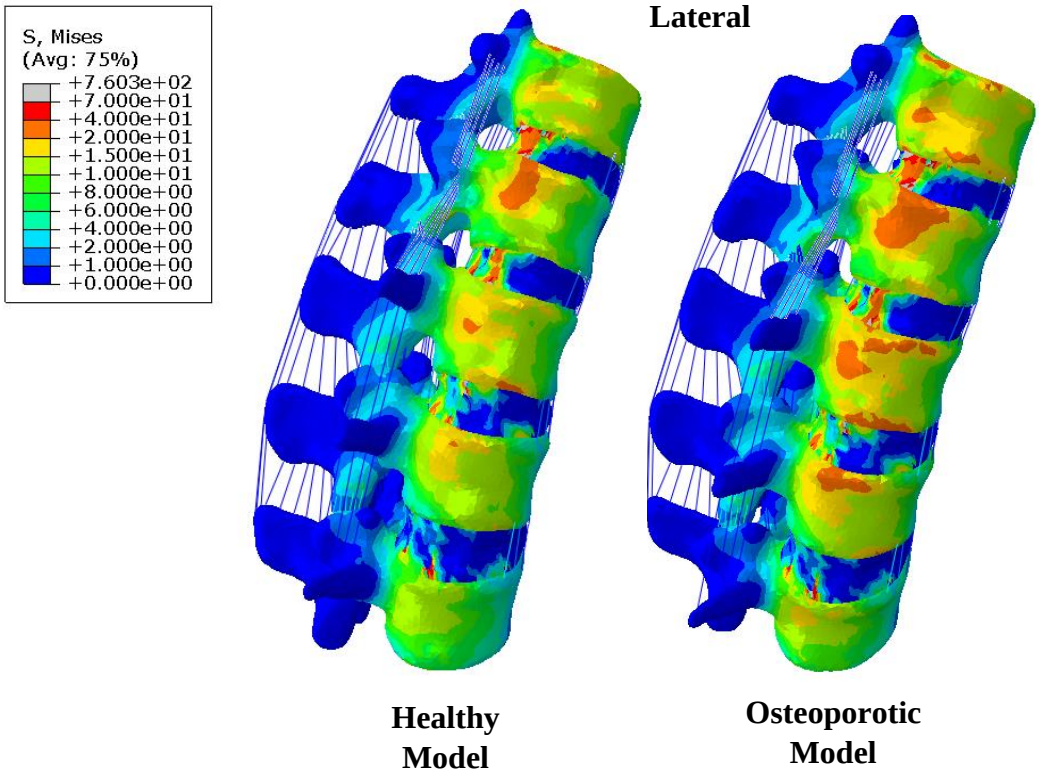

Figure 35 - Von Mises stress distribution of the T11-L3 functional unit for the lateral bending loading mode

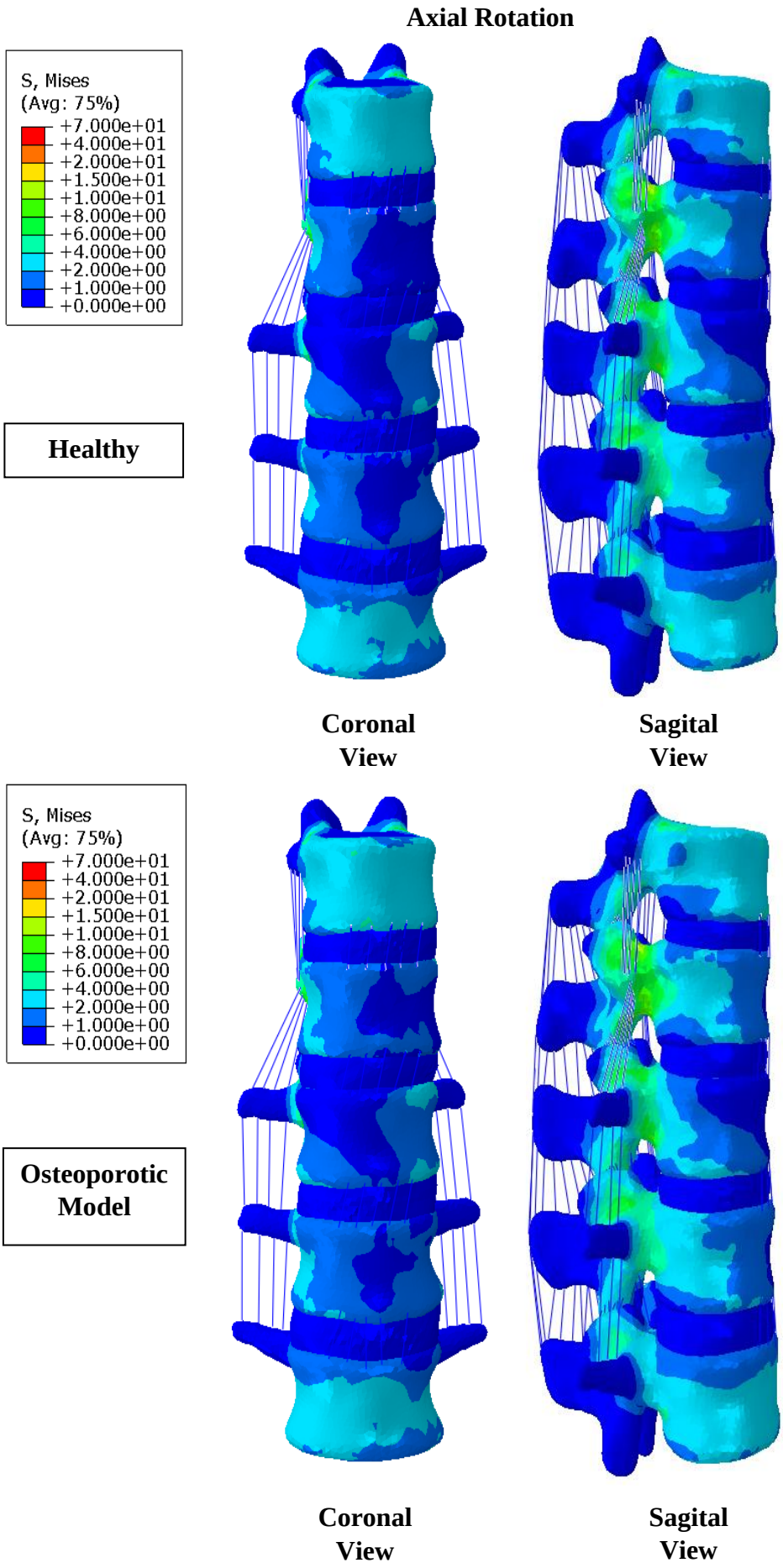

Figure 36 - Von Mises stress distribution of the T11_L3 functional unit for the axial rotation loading mode with two view planes

Chapter 6

Conclusions and Future Works

In conclusion, the data presented confirm an alteration in the stress distribution in the osteoporotic column, resulting from the architecture remodelling which characterize the pathology. These changes result in an increased stress in the cortical bone of the vertebra, particular in the limits of the surface of each vertebra. These results explain the increased risk of bone fracture in patients with osteoporosis, the possibility of discogenic chronic pain, and reinforce the importance of bone remodelling prevention in these cases.

The present work has several limitations, which should be described. First of all, the properties of the bone were altered in order to simulate the bone degeneration in the osteoporotic vertebral column. However, this model-based study is not able to reproduce with accuracy every clinical manifestation and risk factors to osteoporosis, seen in medical practice. As mentioned before, disc degeneration has a close relation with bone degeneration, being one of the factors which may increase the bone deterioration in patients of osteoporosis. Osteoporosis also may have a negative impact on the integrity of the intervertebral discs, accelerating their disintegration. As the intervertebral discs properties were not changed, this relation could not be analysed. The model used as the basis for this work did not present the muscles who support the vertebral column, and which have an important rule in the progression of osteoporosis. The ligaments previously modulated were not include in the present study.

Therefore, in further studies it would be interesting to include a deeper analyses of intervertebral disc degeneration and its relevance in the impact of osteoporosis in the vertebral column. On the other hand, it would be important to investigate the role of other tissues, such as ligaments and tendons, on the progression of the disease. Finally, increments in the model presented may be done in order to better represent the reality of the osteoporotic vertebral spine.

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