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# A finite element analysis of a T12 vertebra in two consecutive examinations to evaluate the progress of osteoporosis

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ABSTRACT

Osteoporosis is a metabolic disease that causes bones to become fragile and be more likely to break. As basic clinical examinations to detect osteoporosis, dual energy X-ray absorptiometry (DXA) and quantitative computer tomography (QCT) are used. In the framework of a typical clinical examination, QCT scans were obtained from the T12 vertebra of an elderly woman and osteoporosis was diagnosed. One year later, new QCT scans were obtained in order to evaluate her clinical condition. Using both sets as primary information, two patient-specific finite element (FE) models were created and analyzed under compressive load. Vertebral bone was treated as orthotropic material and its elastic modulus was set as an indirect function of Hounsfield Units (HU). Commercial software for medical image processing and FE analysis, along with in house codes, were used for the mechanical analysis of the FE models. Alterations in the geometry/shape of the vertebra as well as in the distributions of several mechanical quantities were detected between the two FE models.

As far as the volume of the vertebra is concerned, it augmented by a percentage of 9.7% while the volume of the vertebral body alone increased by 5.6%. In all the maximum values of the mechanical quantities a measurable reduction was observed (axial compressive displacement: 37.9%, von Mises stress: 23.8%, von Mises strains: 15.1%) and all the investigated distributions in the second FE model became smoother. Finally, the percentage of volume with von Mises strains greater than 4500 μstrain dropped from 8.9%, in the first examination, to 4.9% in the second one. Clinically, the prescribed medication seems to have reinforced the structural stability of the vertebra as a whole and through external remodeling the shape of the vertebra changed in a way that the majority of its volume was relieved from stresses and strains of high magnitude.



## 1. Introduction

Considering the aging of the population due to the progress of medical science, medical conditions such as osteoporosis come to the foreground. Osteoporosis has been defined as "a skeletal disease characterized by low bone mass and microarchitectural deterioration of bone tissue, with a consequent increase in bone fragility and susceptibility to fracture" (Consensus Development Conference, 1991) [1].

The hallmarks of osteoporosis, that according to its definition are low bone mineral density and vertebral deformity [2,3], can be determined in clinical environment by various radiographic techniques such as single or dual-photon absorptiometry, DXA and QCT [4], in terms of bone mineral density (BMD) values. BMD is expressed as the number of standard deviations (SD) below the population average for healthy young adults (T-score). The World Health Organization (WHO) study group's definition of osteoporosis is a T-score below −2.5 SD. Patients with a T-score below −2.5 who also have suffered a fragility fracture have severe osteoporosis [5]. In terms of BMD units the threshold for osteoporosis is 0.577 g/cm$^2$ [6].

Although the information provided from typical radiological techniques can lead to the classification of bone specimen according to its BMD, it cannot give sufficient data regarding its mechanical integrity. This can be obtained combining these medical data with mechanical methodologies, such as finite element (FE) analysis in both research and clinical settings.

Mizrahi et al. [7], simulating osteoporosis, created a generic three-dimensional, symmetric, idealized FE model of an isolated elderly human L3 vertebral body and studied how material properties and loading conditions influenced endplate displacement and cortical shell stresses. The mechanical quantities that were reviewed were the axial displacement and the stress components, as well as von Mises stress.

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Finite element models based on three-dimensional reconstruction of QCT scans have been used to quantify damage [8] in vertebrae, to study bone implant systems [9] and to differentiate between vertebrae with and without osteoporosis [10,11]. Polikeit et al. [12] created FE models of vertebral bodies and studied the effect of disc degeneration, degree of anisotropy of bone material and osteoporosis to the stresses and strains within the functional spinal unit (FSU). Using FE modeling of the lumbar vertebral bodies, Homminga et al. [13] concluded that the load carried by the vertebral cortex was not affected by osteopenia or osteoporosis and it was increased with the degree of disc degeneration. His conclusions were drawn through the evaluation of the principal strains, as well as the strain energy density (SED) values. Kopperdahl et al. [14] proposed that areas of high SED in the vertebra can be anticipated to be locations of damage using FE models of vertebral cross-sections.

With the evolution of the CT-scanners and the possibility of using μCT, voxel elements have been introduced as a tool for the mechanical analysis of vertebrae specimens. Eswaran et al. [15], using voxel elements, monitored the distributions of von Mises stress in order to understand the micro-mechanics of the human vertebral body and especially the cortical shell removal. The same group [16] proposed a way to locate parts of bone tissue at high risk of initial failure during compressive loading in the vertebral body using maximum and minimum principal strains.

In the present work, two FE models of a T12 vertebra belonging to an elderly female patient have been created. Each one corresponded to a set of CT scans performed, as a typical examination for the evaluation of the condition of the patient, in the interval of one year. The objectives of this simulation were (a) to study the mechanical behavior of the vertebra in each case, (b) to review mechanical quantities that can be used as indices of structural integrity and (c) to compare the mechanical analysis findings with the medical ones.

## 2. Materials and methods

### 2.1. Subject

The subject was a volunteer woman suffering from postmenopausal osteoporosis (menopausal age of 40) that developed a recent non-traumatic wedging of the T12 vertebra. At the time of the vertebral fracture her T-score at the lumbar spine was −4.81 SD. According to the WHO and her T-score, she was classified as having severe osteoporosis [5]. She was under treatment with bisphosphonates for the last ten years. There was a mild kyphosis of the spine and no findings suggesting secondary cause for the development of osteoporosis. At the time of the first examination she was in the age of 70, her recent height was 162 cm and her weight was 70 kg. One year later, at the time of the second examination, her height was unaltered and her weight was 72 kg.

### 2.2. CT scanning

Both CT scan sets of the T12 vertebra were obtained in a High Resolution Computed Tomography (HRCT) (GE Medical systems Highspeed DX/i). A lateral scout view was used to localize the T12–T11 vertebral levels and upper and lower endplates. Scanning was performed from the middle of the T11 vertebral body cephalad to above the middle of L1 vertebral body, for the demonstration of the whole vertebral body of T12, including the spinal process, transverse processes and superior and inferior articular processes.

The abovementioned volume was encompassed with: 0.8 mm thick contiguous axial slices, table speed: 2 mm/s, reconstruction interval: 0.4 mm at settings of: 120 kV and: 170 mA. Images were reconstructed using both the standard (soft tissue) and high-resolution/ultra-high-resolution algorithm. A $512 \times 512$ image matrix was used for FE mesh generation.

To correlate the CT measurements to BMD, a single-slice spinal QCT scan was performed. In both cases, the subject was scanned simultaneously with a bone mineral reference liquid $K_2PO_4$ calibration phantom. The mineral calibration phantom was compared with an ellipsoid region of interest in the centre of the vertebral bodies (spongy BMD) and the cortical BMD was measured using QCT assisted by an automatic contour finding program [17,18].

### 2.3. Finite element modeling

#### 2.3.1. Creation of the geometry of the vertebra

The anatomically and geometrically accurate three-dimensional FE models of the T12 vertebra for both clinical examinations were developed from the CT scans obtained in the form of DICOM (Digital Imaging and Communication in Medicine) files. Both solid models were developed in two stages: surface creation and solid definition.

The CT data was imported in the MIMICS software v. 8.1 (Materialise, Belgium). This software generates high-resolution 3D renderings. A thresholding HU value was set to define the boundaries of the vertebrae and their edges were traced automatically. Both renderings contained parts of the upper and lower vertebrae, which were graphically removed by the user from the final outcome.

Any discontinuities in the bone were manually filled in this part of the process, so as to result in continuous subjects describing the outer surfaces as accurately as possible. Thereafter, two stereolithography files (stl), containing the outer surfaces of the 3D rendering in form of triangles were extracted.

Both stl files were created with the use of the same options for the quality of the containing surfaces. After necessary changes, they were imported in the multiple-purpose commercially available FE modeling software ANSYS v.10 (ANSYS, Inc. Pennsylvania) where one solid model, consisting of one volume for each vertebra has been created.

#### 2.3.2. Mesh generation

Mesh generation includes the definition of the number of the elements, as well as their type and size. Three-dimensional meshes with tetrahedral 10-nodded quadratic elements (solid92) were constructed using an automatic mesh function of ANSYS. This type of element is able to give a good and accurate rendition of the surface geometry. All meshes were adjusted to prevent element distortion. A mesh convergence study was performed to ensure adequate numerical convergence of the results [19].

#### 2.3.3. Material properties and attribution

In order to simulate the inhomogeneity of bone material distribution, the elastic modulus of each FE was determined indirectly from the CT data. Pathologies of the spine related to loss of BMD are introduced through both cortical and cancellous bone [20].

According to the literature, empirical relationships connecting HU to BMD were obtained. Subsequently, BMD values ($\rho_{QCT}$, g/cm$^3$) were converted into elastic modulus values ($E$, MPa), using site specific correlations between the elastic modulus and QCT-derived mineral density for cortical and trabecular bone [11,21,22].

The centroid of each FE was calculated. A corresponding group of eighteen pixels (nine in the CT scan below and nine in the one above the centroid) was defined and the weighted average of their HU was calculated. The average HU were separated in groups corresponding to different material properties.

In a parametrical study performed by Provatidis et al. [19], it was shown that the optimum number of groups representing different materials is nine. This study performed the investigation of the influence of mesh quality and number of materials used to simulate osteoporosis in FE models of vertebrae.