3D Parametric Finite Element Model for the Mechanical Simulation of Vertebrae with Metastatic Lesions

Jaime Muñoz-Allué[1], José Manuel García-Aznar [1], María Ángeles Pérez[1]

[1] Multiscale in mechanical and biological engineering (M2BE)
Instituto de Investigación en Ingeniería de Aragón (I3A)
Universidad de Zaragoza, Mariano Esquillor s/n, 50018, Zaragoza, Spain.
Tel. +34-976762707, e-mail: *j.munoz@unizar.es*

Abstract

Bone metastases in the spine are very common in cancer patients. A 3D parametric model based on the finite element (FE) method has been developed to study various types of metastatic lesions. Several *ex vivo* experimental cases were reproduced, and the impact of the bone-tumour interface was investigated.

Introduction

Bones are frequently affected by metastatic lesions, particularly from high incidence cancers such as prostate, lung, and breast cancers, which exhibit a notable predilection for bone metastasis [1]. Bone metastases in the spine occur in 70% of cases, posing a significant risk of vertebral fracture [2]. Clinical soring systems are used but are not sensitive and specific enough [3]. Computational modelling offers a valuable tool for investigating of how metastatic lesions affects the mechanical stability of the spine. This study aims to analyse the influence of different vertebral metastases types, specifically focusing on lytic and blastic lesions. The study also considers the impact of the bone-tumour interface through modelling its rupture or mechanical failure. To achieve this, a parametric model for patient-specific analyses has been built. Additionally, experimental *ex vivo* data from [4] are used to validate the 3D parametric model of metastatic vertebrae.

Material and methods

A 3D parametric model based on the FE method has been developed. The model consists of two vertebrae, where the lower one simulates a radiologically healthy vertebra (control), and the upper one simulates a vertebra affected by the metastatic lesion. The vertebrae are separated by an intervertebral disc (E=10 MPa, v=0.49) and a distinction is made between cortical (E=2,000 MPa, v=0.3) and trabecular bone (E=750 MPa, v=0.3). As a first approximation, all materials are assumed to be homogeneous, isotropic and linearly elastic.

This parametric model enables the simulation of diverse vertebral geometries, incorporating various sizes and locations of lesions. This model is based on a python script running in Abaqus. Therefore, through the extraction of pertinent measurements from medical images, realistic cases can be reproduced and examined under different loading conditions, facilitating patient-specific studies (Figure 1).
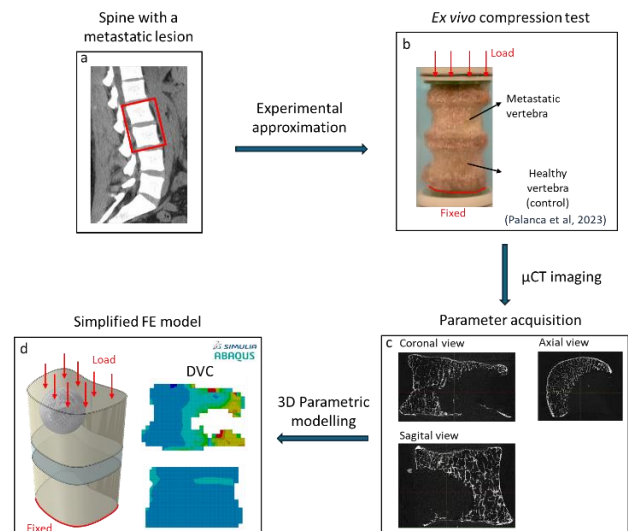

Figure 1: Procedure for assessing 3D parametric FE modelling. From a metastatic spine (a), the affected vertebra and an adjacent vertebra as control are selected to do an *ex vivo* compression test (b). CT scans are performed before and after the test and to obtain the strains produced using Digital Volume Correlation (DVC) and to observe the fracture site [4]. In addition, the necessary geometrical parameters are extracted from these images (c). Finally, by introducing these parameters in the parametric modelling algorithm a simplified FE model is obtained of the experimental test, and the resulting strains of the simulation can be compared with those of DVC (d).

The mechanical properties of the lesion, specifically the Young's modulus and Poisson's ratio, have been modified to analyse different types of lesions. Furthermore, the influence of the bone-tumour interface has been studied by simulating both bonded and debonded interfaces, employing a tie constraint and a frictionless contact, respectively.
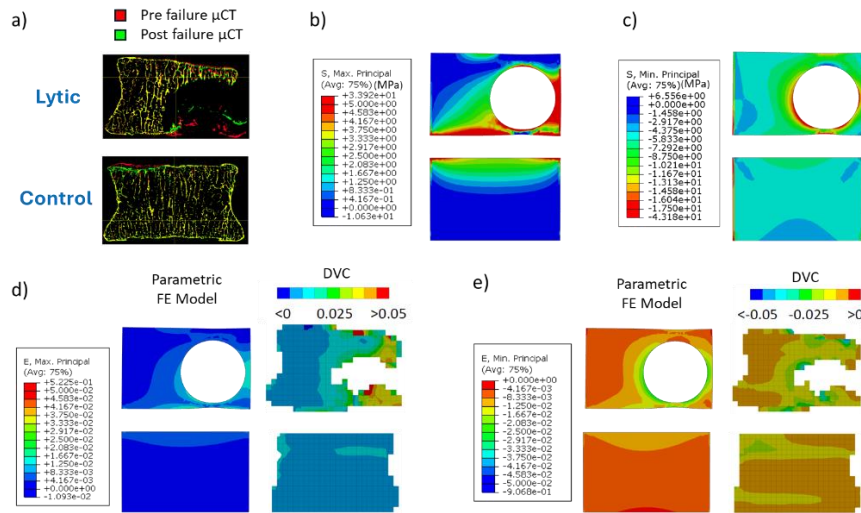
Figure 2. Lumbar vertebral segment (L2-L3) with L2 affected by a lytic metastatic lesion. a) μCTs before and after fracture following the experimental test. Maximum (b) and minimum (c) principal stresses (MPa) resulting from the simulation of the parametric model. d) Maximum (d) and minimum (e) principal strains from the simulation with the parametric model (left) and DVC (right).

Results

The developed parametric model successfully reproduced the results from two *ex vivo* compression test (Figure 2). It has been observed that lytic lesions exhibit maximum principal stresses in the vertebra at the upper and lower regions of the lesion, while blastic lesions behave oppositely, with stresses concentrating in the vertebra at the anterior and posterior regions of the lesion (Figure 3). In some cases, lytic lesions could be approximated by the absence of bone. Through the study of the bone-tumour interface, it has been noted that its mechanical failure does not have a significant influence on the mechanical behaviour of the vertebrae for lytic lesions but can profoundly modify it for blastic lesions.
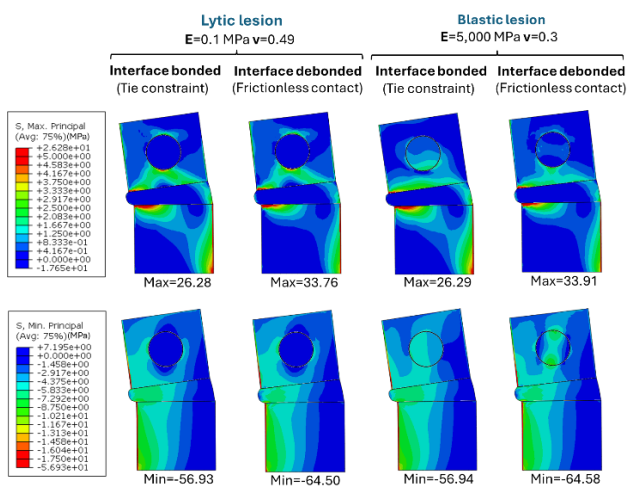

Figure 3. Maximum and minimum principal stresses (MPa) from simulations with the interface bonded using a tie constraint and debonded with contact for lytic (left) and blastic lesions (right).

Conclusions

The parametric model enables reproducible patient-specific simulations. Additionally, the material properties of different types of lesions play a significant role in the response of vertebrae. Furthermore, the bone-tumour interface further modulates vertebral behaviour based on bonding conditions, particularly in blastic lesions, where it is expected that the actual influence of the interface falls within an intermediate range, neither fully bonded nor completely loose.

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