IMAGE TO ANALYSIS PIPELINE: SINGLE AND DOUBLE BALLOONS KYPHOPLASTY

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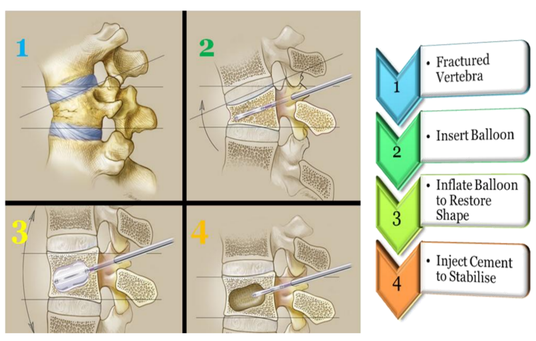
INTRODUCTION

Treating fractures of the spine is one of the major challenges for the medical community with an estimated 1.4 million fractures per annum worldwide (Johnell and Kanis, 2006).
Two modern techniques for treatment of the fracture vertebrae are Vertebroplasty and Kyphoplasty.

FIGURE 1

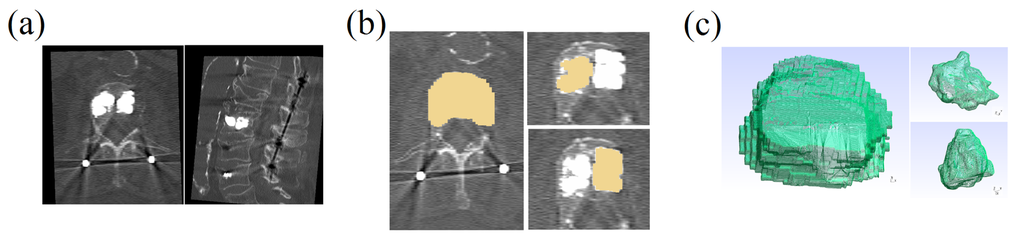


The figure is extracted from (Purcell et al., 2013).
In the Kyphoplasty, two or four balloons are inserted into the fractured vertebra and inflated to expand the compressed vertebra to the normal vertebra's height. Then, they are deflated and provide a space in the middle of the vertebra. Finally, the bone cement (called Poly-Methyl-Methacrylate) is injected slowly to stabilize the fractured vertebra and the height restoration.

PIPELINE

- Segment and reconstruct medical images (CT-Scan in DICOM format) into a 3D geometry.
- Perform some geometry processing operations: smoothing, collapse and refinement and adaptively re-meshing.
- Simulate the biomechanics model (linear elastic) via finite element analysis.
- Perform the fracture analysis for yield criterion of Von Mises stress.
- Analyze the uncertainty propagation on the Von Mises Stress due to lack of information in material properties and loading.

SEGMENTATION

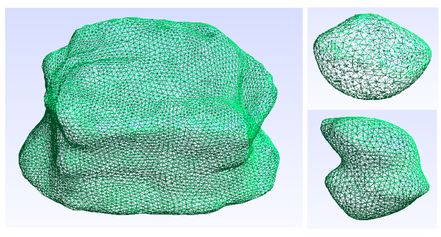


Using the open-source software `3DSlicer` (Fedorov et al., 2012), the procedure is the following: (a) importing the radiotherapy planning with Computed Topography (CT) ; (b) determining the fractured vertebra as region of interest (ROI) and repeating the same procedure for every injected cement; (c) creating a 3D surface model of segmented images and exporting them in the STL format.

GEOMETRIC PROCESSING OPERATIONS

The robust geometric processing operations are performed using `MeshMixer` (Schmidt and Singh, 2010) to deal with the following issues: isolated unphysical island, degenerate triangle, irregular shape with cuspid.

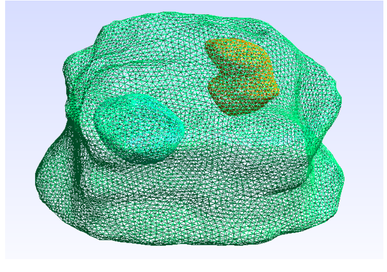
FIGURE 3



`MeshMixer` smooths, removes the degenerate elements of the surfaces and adaptively re-meshes.

MESH GENERATION

FIGURE 4



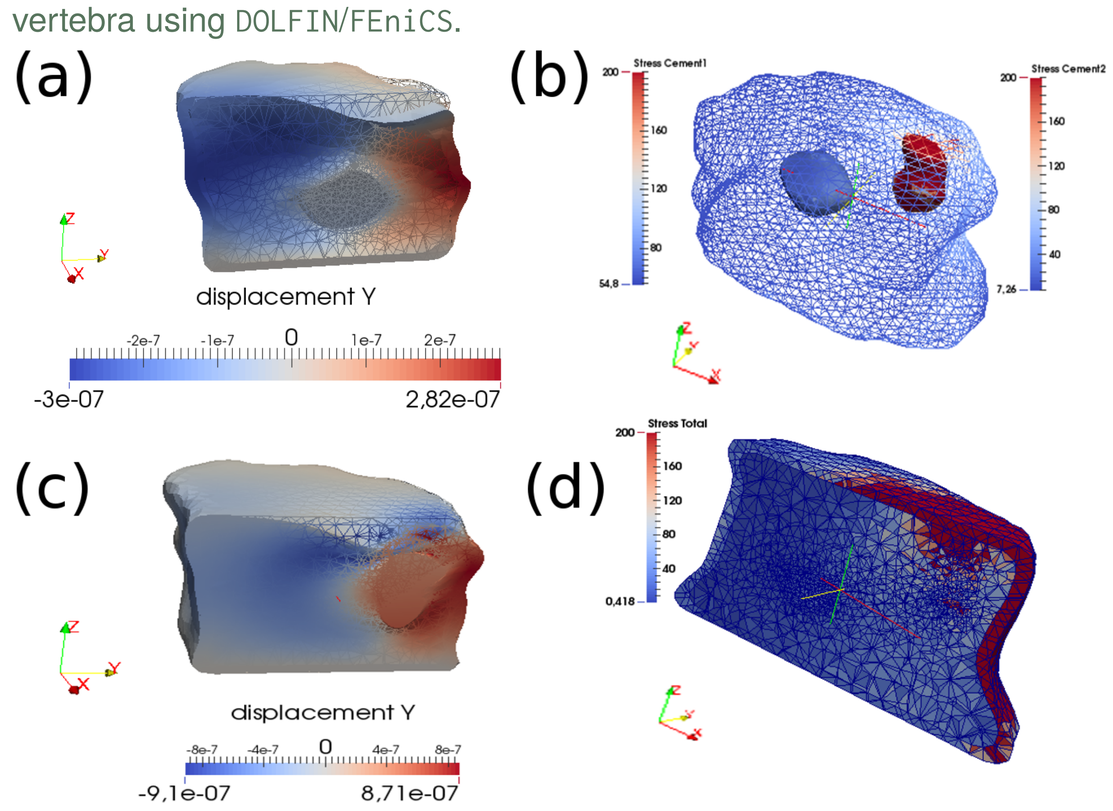
The smoothed surfaces of vertebra and the cement regions are merged in the `GMSH` (Geuzaine and Remacle, 2009). In addition, using `GMSH` the volumetric mesh is generated using 3-D Delaunay algorithm and both the surfaces and the volumes of each region are labeled.

REFERENCES

Purcell, Philip et al. (2013). "A parametric finite element analysis of the compacted bone-cement interface following balloon kyphoplasty". In: *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*.

FINITE ELEMENT ANALYSIS

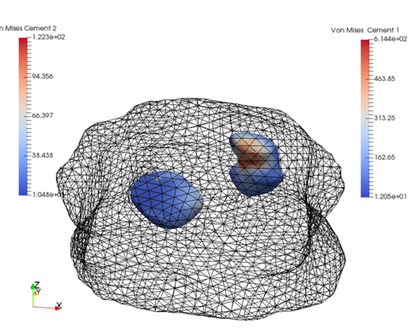
Finite element analysis shows the elastic behavior and the strength of the vertebra using `DOLFIN/FEniCS`.



The figure highlights the deformation within the regions of vertebra that contain (a) the first cement and (b) the second cement; (c) stress distribution on cortical and cements interface; (d) (d) total stress.

FRACTURE CRITERION

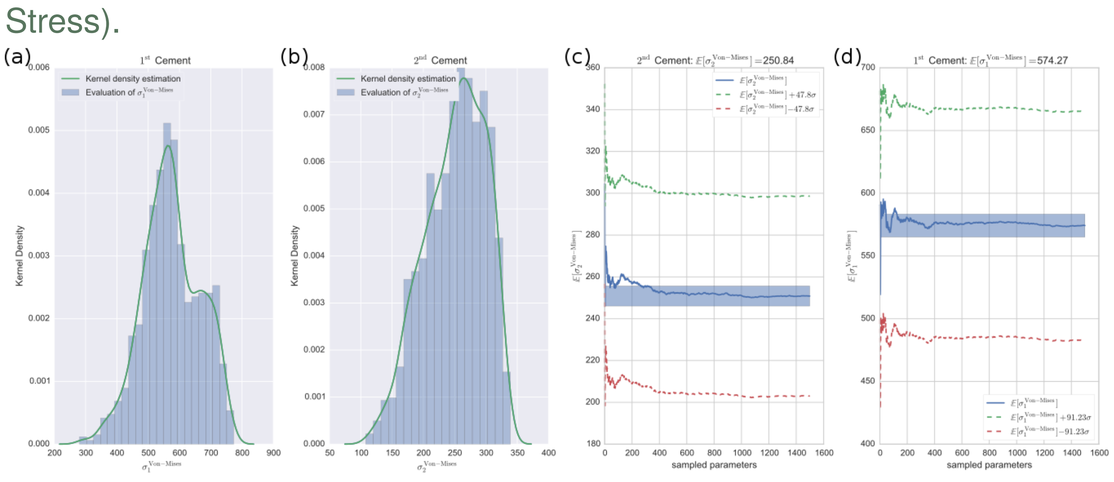
FIGURE 6



At the post-augmentation stage, the quantification of the subsequent vertebral fracture risk in is investigated by the evaluation of the Von-Mises stress over the injected cement.

UNCERTAINTY QUANTIFICATION

Using Monte-Carlo technique (Caflisch et al., 1998), it is possible to investigate the effects of parameter variability and measurement uncertainty (stiffness and traction support) on model outputs (Von-Mises Stress).



Monte-Carlo consists in computing the Von Mises stress for each sampled heterogeneous physical parameter, which is treated as the random variable with Beta density kernel, and approximate the expectation by sample averages;(a) The expectation value vs the sampled parameters ;(b) The kernel density of the quantity of interest over the cement interface.

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Caflisch, Russel E. et al. (1998). "Monte Carlo and quasi-Monte Carlo methods". In: *Acta Numerica* 7.1, p. 1.

Fedorov, Andriy et al. (2012). "3D Slicer as an image computing platform for the Quantitative Imaging Network." In: *Magnetic resonance imaging* 30.9, pp. 1323–41.

Geuzaine, Christophe and Jean-François Remacle (2009). "Gmsh: a three-dimensional finite element mesh generator with built-in pre-and post-processing facilities". In: *Internation Journal for Numerical Methods in Engineering*, pp. 1–24.

Johnell, O. and J. A. Kanis (2006). "An estimate of the worldwide prevalence and disability associated with osteoporotic fractures". In: *Osteoporosis International* 17.12, pp. 1726–1733.

Schmidt, Ryan and Karan Singh (2010). "Meshmixer". In: *ACM SIGGRAPH 2010 Talks on - SIGGRAPH '10*. New York, New York, USA: ACM Press, p. 1.