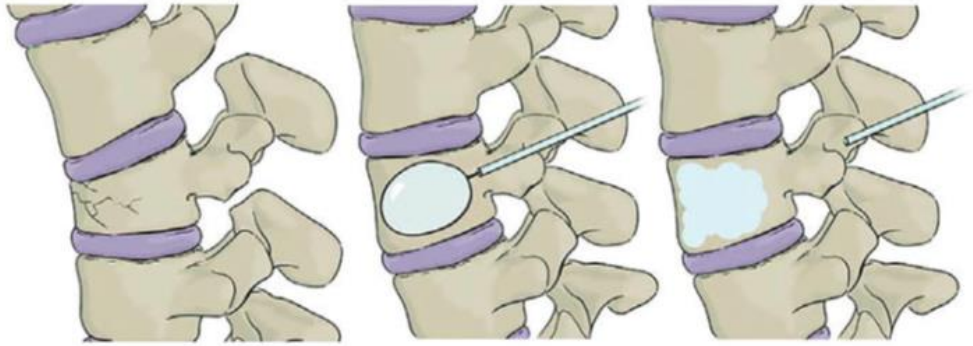
Modelling for spinal surgeries

ESR5: Marco Sensale

Introduction

[2]



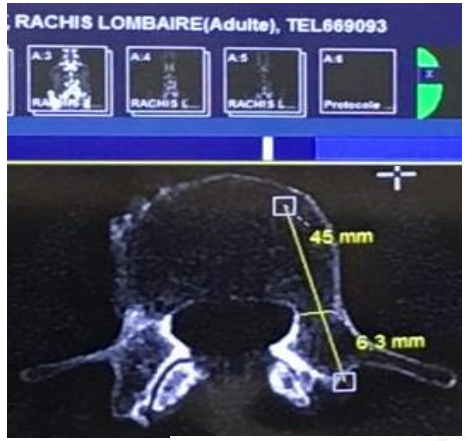
[3]

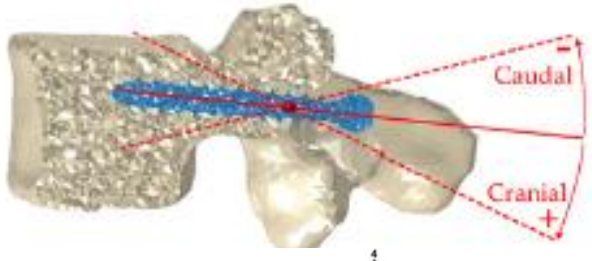
Vertebral fractures

- ≈900.000 annual cases in the US [1]
- Osteoporosis, high and low energy traumas, metastases ecc.
- Minimally invasive techniques: posterior fixation, vertebroplasty, kyphoplasty

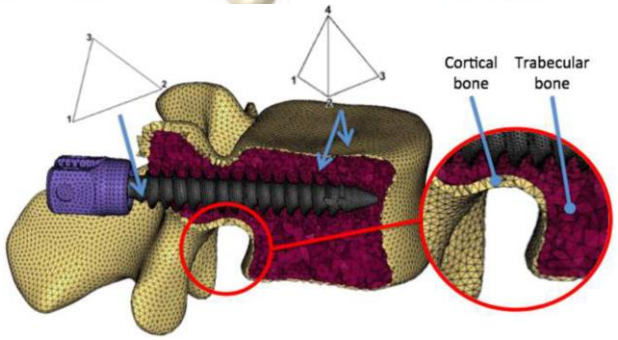
[1] Melton et al. 1997, [2] Kumar et al. 2005, [3] Ebeling et al. 2019

Introduction





[1]



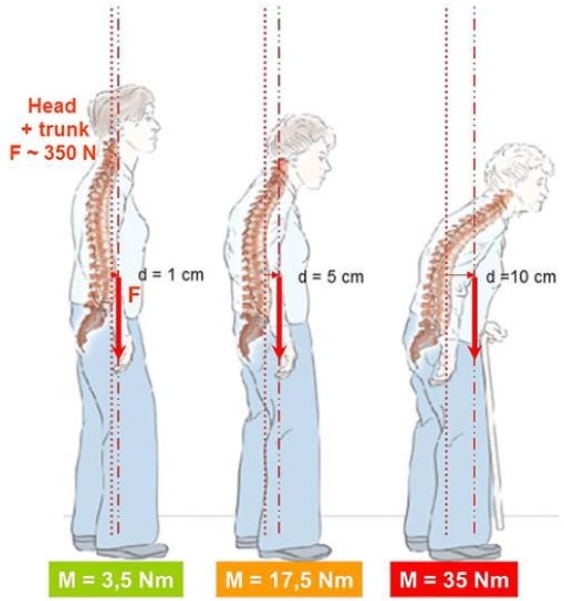
[2]

Posterior fixation

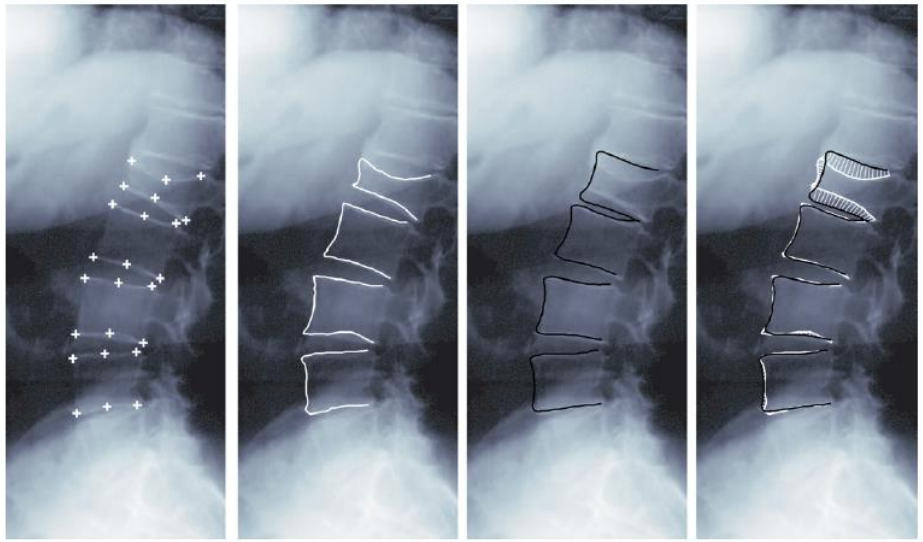
- Post-operative complications: pain, kyphosis, loss of reduction etc.
- Parametric FE models: absence of verification, unestimated effect of parameters, high computational time

[1] Molinari et al. 2021, [2] Bianco et al. 2020

Introduction



[1]



[2]

Vertebral augmentation

- Cement leakage, adjacent vertebral fracture, kyphosis, loss of reduction etc.
- No geometric information before the fracture
- Pre-fracture shape predicted only in 2D case

[1] Pesce et al. 2013, [2] de Bruijne et al. 2007

Objectives

- To verify subject-specific CT-based FE models of the human vertebra with two pedicle screws
- To evaluate their sensitivity to the geometrical properties of the screws

Study #1

- To explore if reduced order models (ROM) can be used to improve the efficiency of parametric FE models to optimize the screws' properties

Study #2

- To develop and evaluate a methodology to predict the shape of the pre-fracture L1 from adjacent vertebrae

Study #3

ORIGINAL RESEARCH article

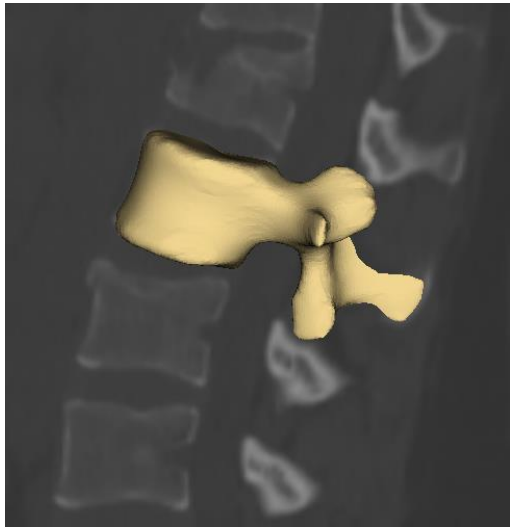
Front. Bioeng. Biotechnol., 10 March 2021 | https://doi.org/10.3389/fbioe.2021.643154

frontiers in Bioengineering and Biotechnology

Patient-Specific Finite Element Models of Posterior Pedicle Screw Fixation: Effect of Screw's Size and Geometry

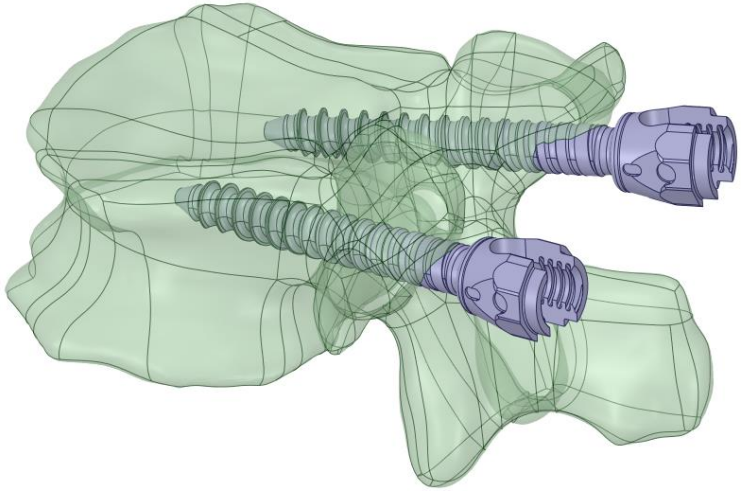
M. Sensale[a,b], T. Vendeuvre[c,d], C. Schilling[e], T. Grupp[e,f], M. Rochette[a], E. Dall'Ara[b]

Methods

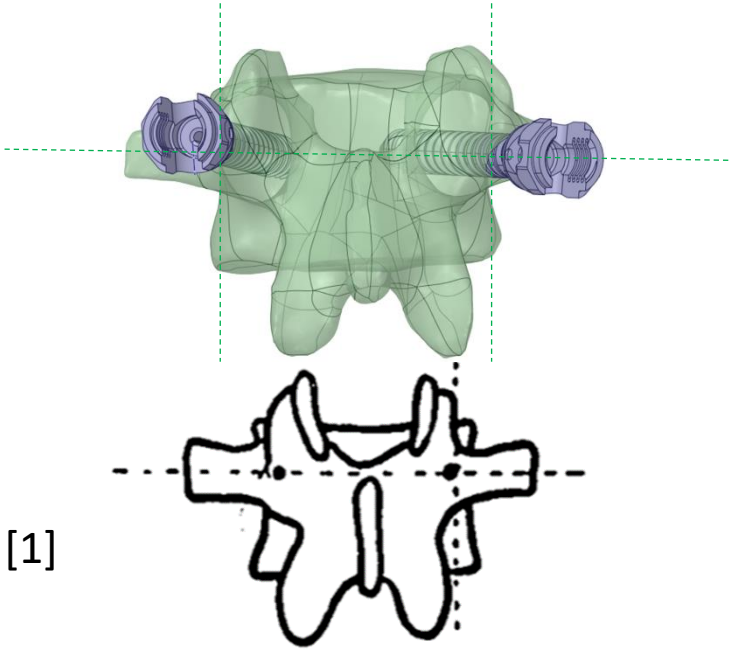


Segmentation
3D Slicer

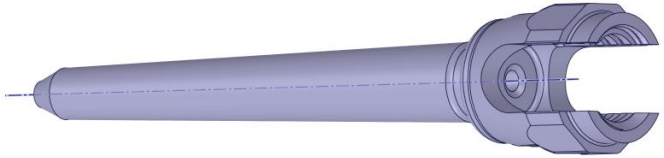
Pt	Voxel size (mm^3)	Level
#1	0.98 x 0.98 x 1.25	L2
#2	0.88 x 0.88 x 1.00	L3
#3	0.68 x 0.68 x 1.00	L4



CAD modelling
SpaceClaim



[1]



Simplified screw

Real Aesculap® S4® Element MIS
Monoaxial screw

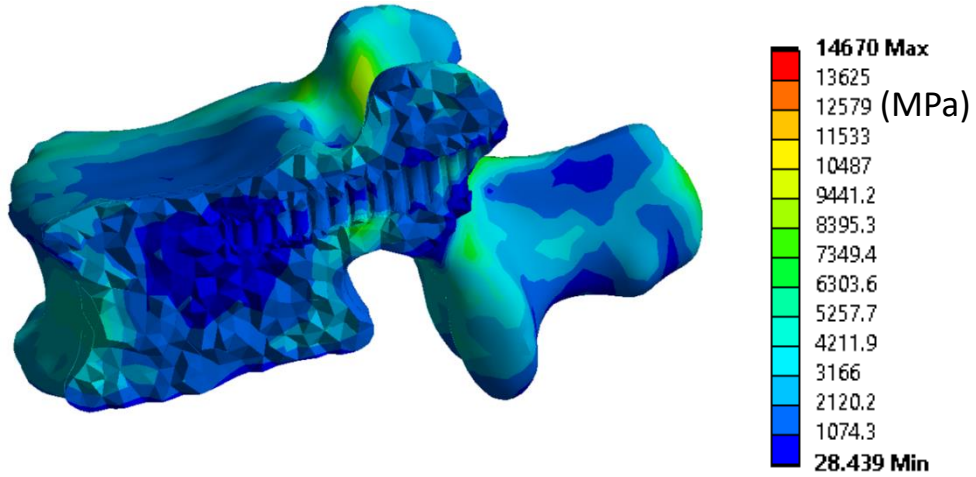
[1] Gertzbein et al. 1990

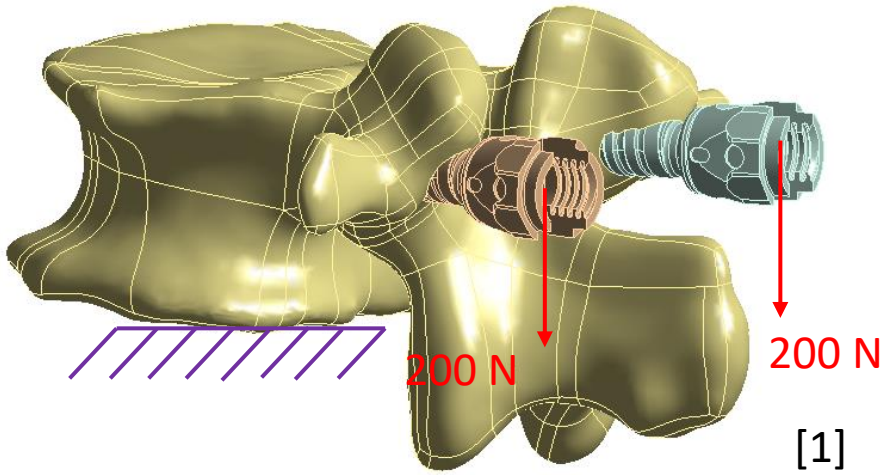
Methods

Bone:
- Heterogeneous
- Isotropic
- Linear elastic (v = 0.3)

Screws:
E = 102 GPa,
v = 0.36 (Titanium)

Screws-bone interface:
bonded



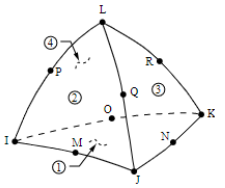


[1]

[1] Rohlmann et al. 1997

Methods

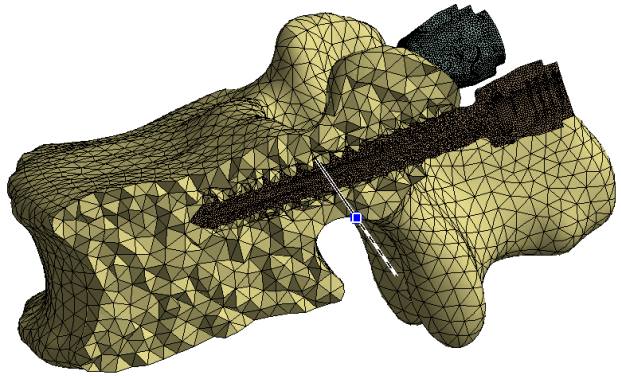
T10



- Verification for optimal screw size (D = 6.5 mm, L = 45 mm):

Max element size

- Screws: (0.4 mm – 1.2 mm)
- Bone: (0.9 mm – 3.0 mm)



Methods

- Verification for optimal screw size (D = 6.5 mm, L = 45 mm):

Max element size
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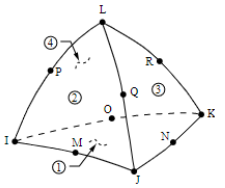
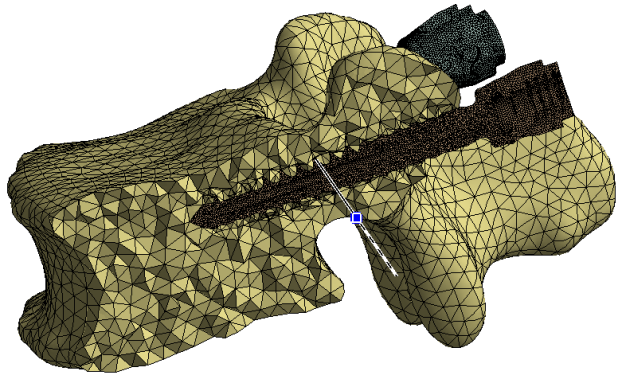
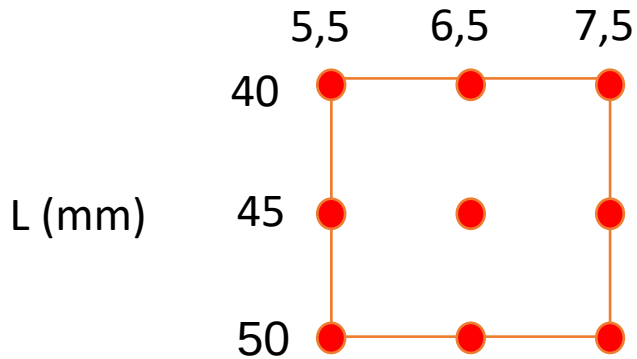
T10





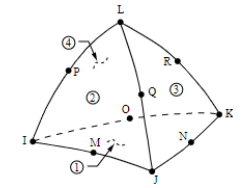
- Sensitivity analysis on Diameter and Length

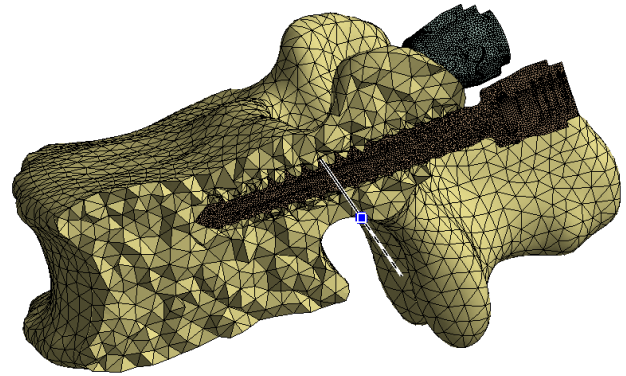


Methods

- Verification for optimal screw size (D = 6.5 mm, L = 45 mm):

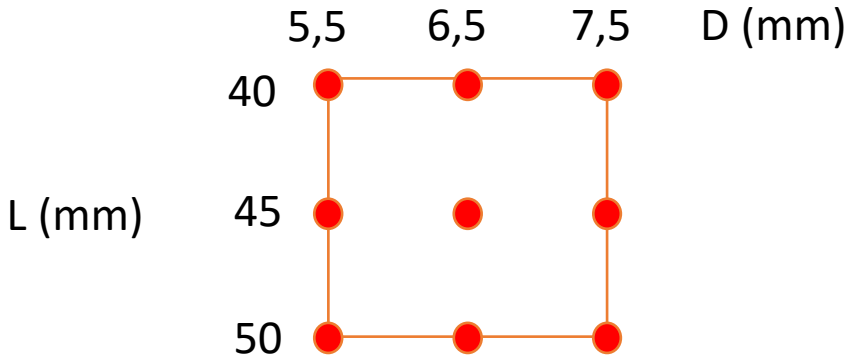
T10



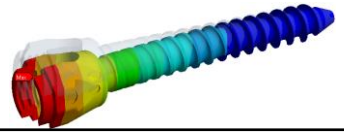
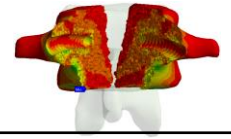


Max element size
- Screws: (0.4 mm – 1.2 mm)
- Bone: (0.9 mm – 3.0 mm)

- Sensitivity analysis on Diameter and Length

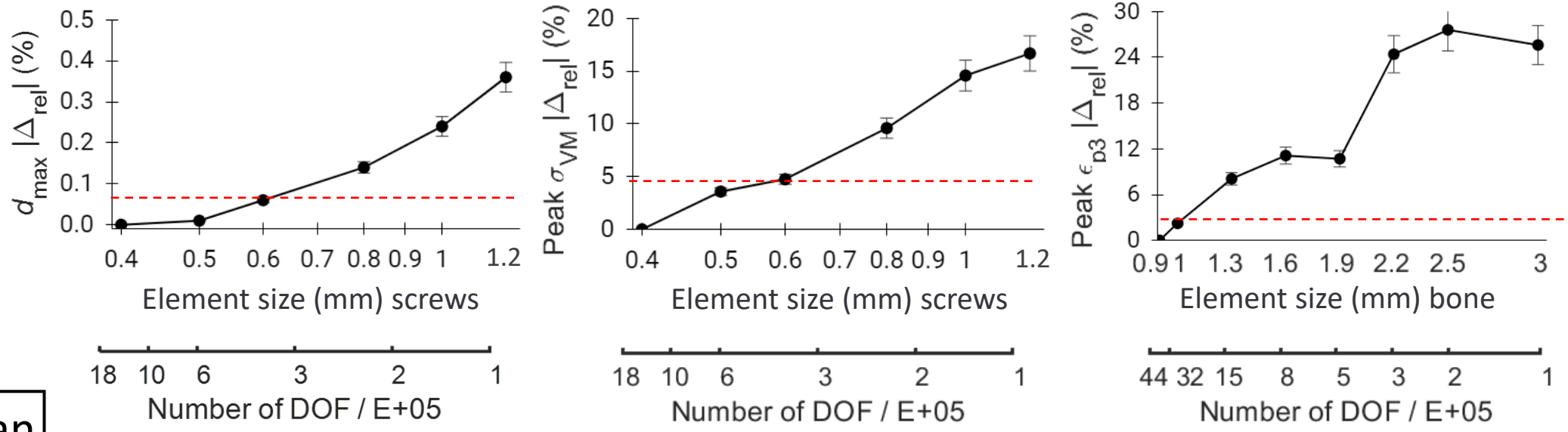


Metrics

Deflection Screw		σ_{VM} Screw		ε_{p3} Bone	

Results

Deflection Screw		σ_{VM} Screw		ε_{p3} Bone	



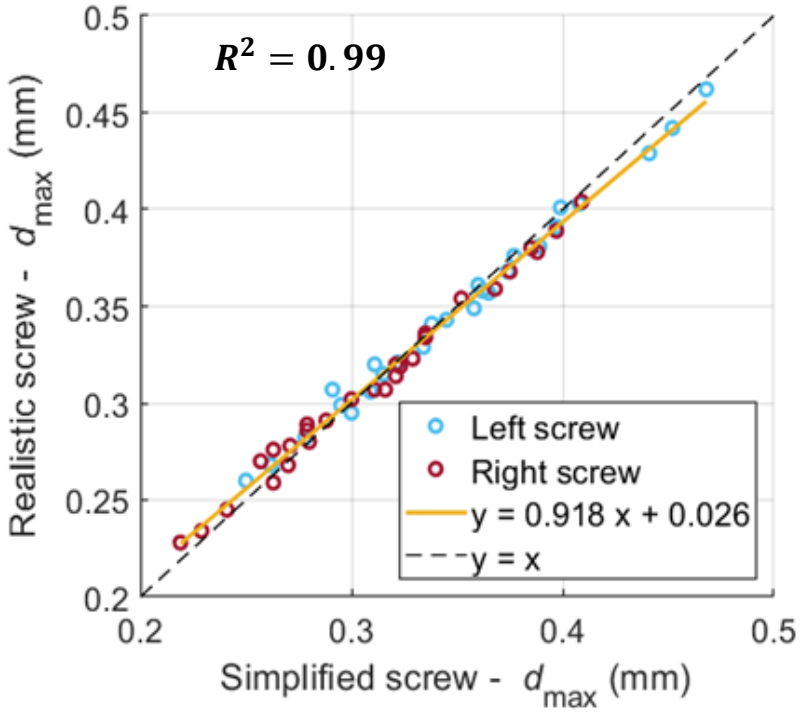
– Mean

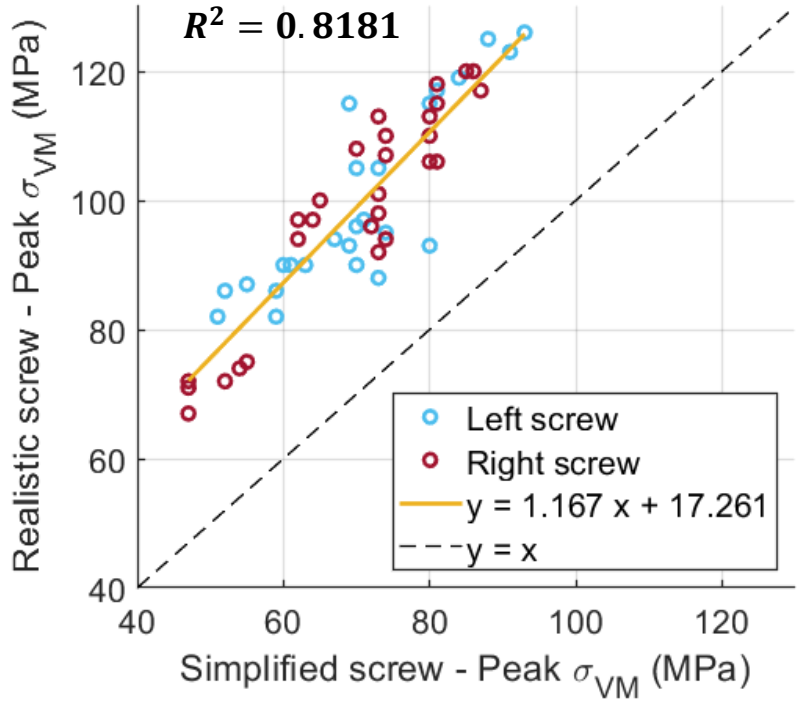
Chosen elemet size of 1.0 mm for the vertebra and 0.6 mm for the screws

Results

		Diameter		
		7.5 mm	6.5 mm	5.5 mm
Length	40 mm	-10%	5%	21%
	45 mm	-16%	REF	18%
	50 mm	-20%	-3%	15%

- *deflection* screw
- σ_{VM} screw
- ε_{P1} bone





Conclusions

- Element size of 0.6 mm in the realistic screw and 1.0 mm in the bone

  ➔ relative differences ≤ 5%

- Relative differences similar for realistic and simplified screws

- Diameter more important than the length of screws

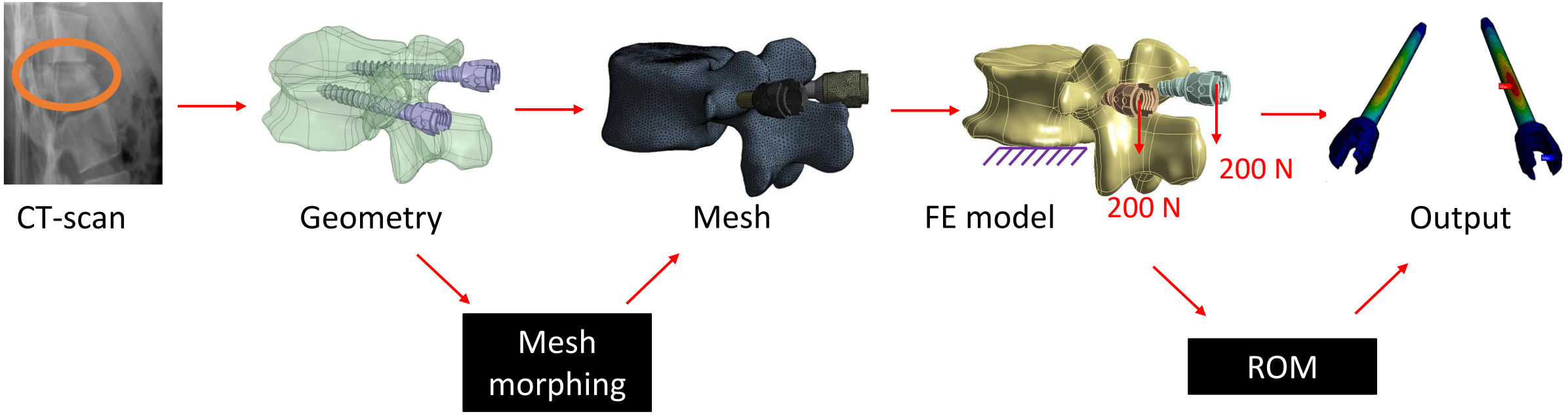
Exploration of Reduced Order Modelling applied to FE models for studying the effect of the screws' size and orientation

M. Sensale[a,b], L. Geronzi[a,c], M. Biancolini[c,d], T. Vendeuvre[e], M. Rochette[a], E. Dall'Ara[b]

[a]ANSYS, France; [b]University of Sheffield, UK; [c]University of Rome "Tor Vergata", [d]RBF Morph srl, Italy; [e]Poitiers University Hospital, France

Presented at: ESB 2021 - JULY 11-14, 2021 - 26TH CONGRESS OF THE EUROPEAN SOCIETY OF BIOMECHANICS

Methods

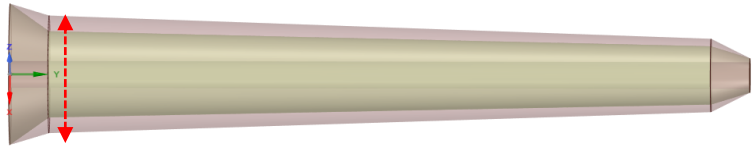


- ROM of the deflection in the screws
- ROM of the von Mises stress in the screws
- ROM of the minimum principal strain in the bone

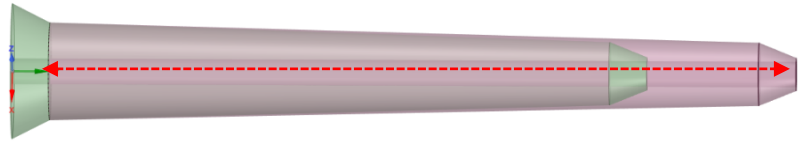
Methods

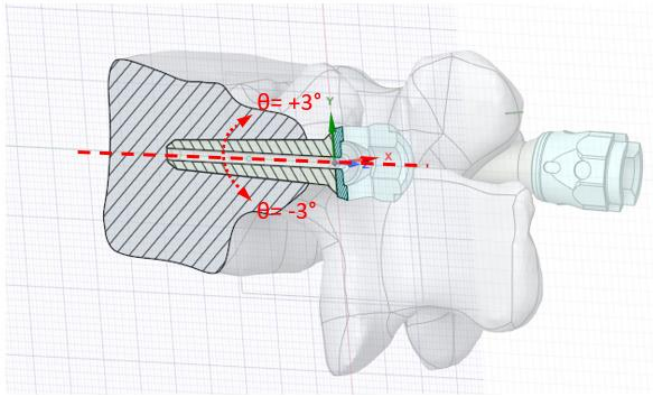
4 shape parameters:
D, L, θ, φ

D ≡ (5.5, 7.5) mm

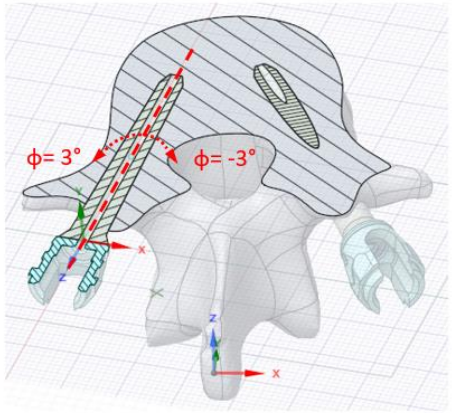


L ≡ (40, 50) mm

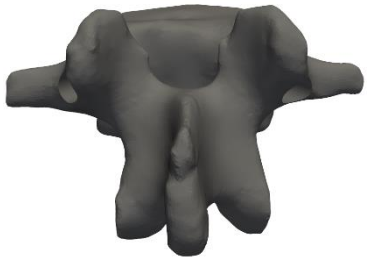




θ ≡ (-3°, 3°)



φ ≡ (-3°, 3°)



CAD update
- Change D and L of screws
- Rotate screws
- Boolean subtraction

Meshing

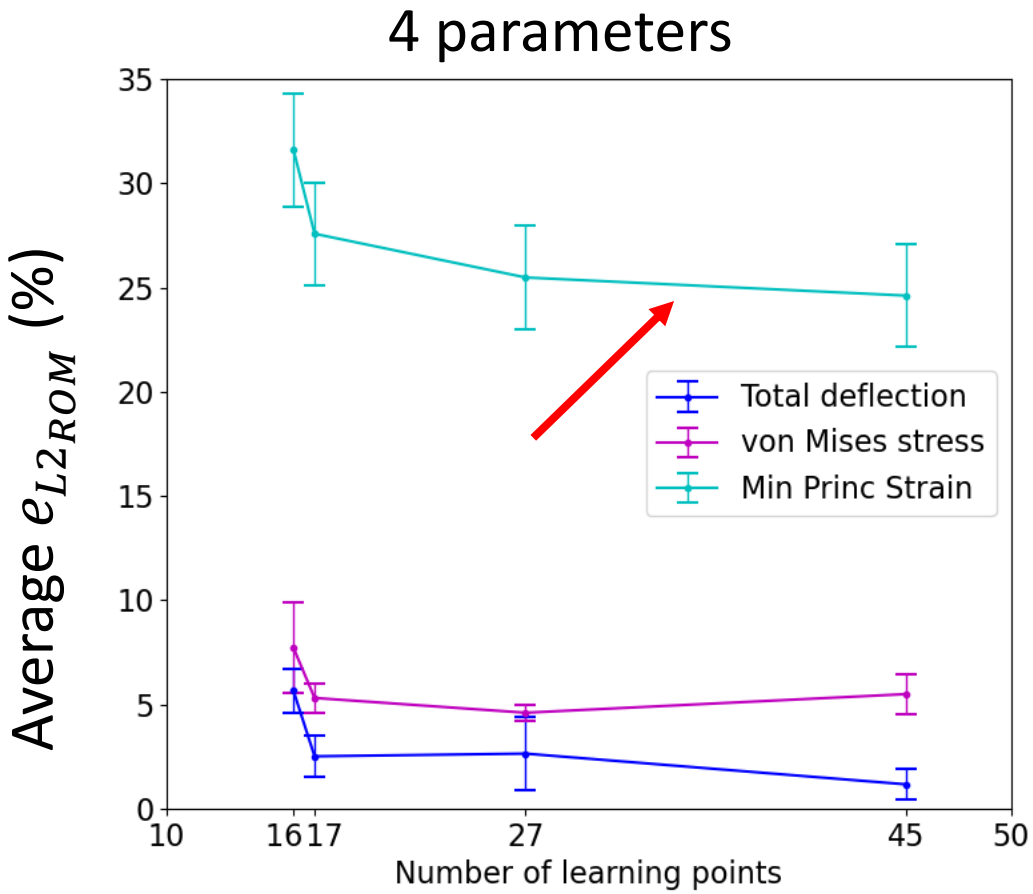
Meshing

Mesh morphing
- Change D and L of screws
- Rotate screws

(rbf-morph)™

Results

$$e_{L2_{ROM}} = \frac{\|X_{ROM} - X_{FE}\|^2}{\|X_{FE}\|^2}$$



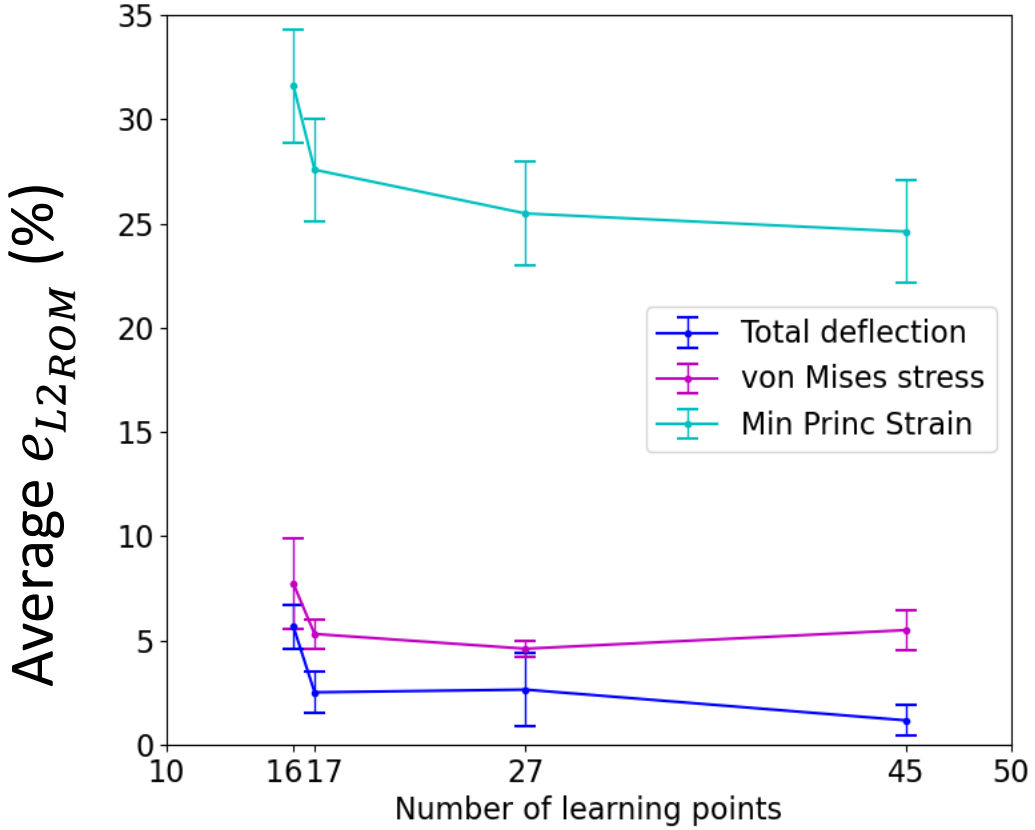
Factors influencing the performance of the ROM:

- Remeshing of the vertebra
- Heterogeneous properties
- Frictional interface

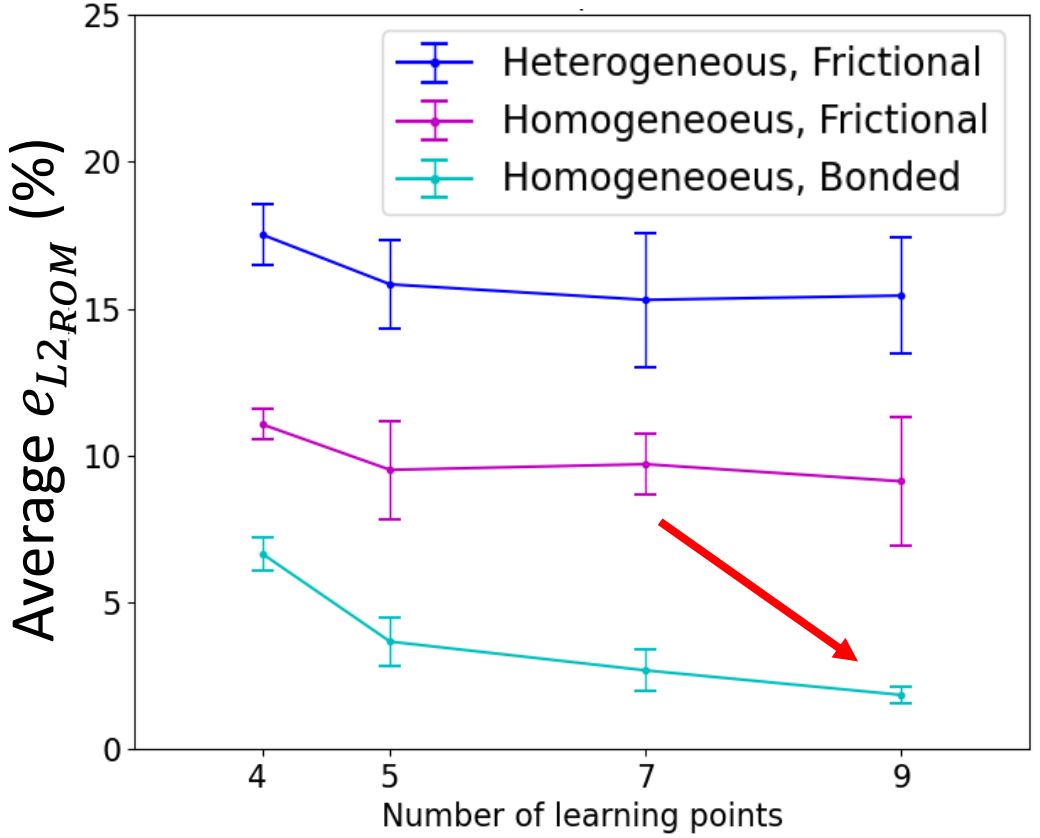
Results

$$e_{L2_{ROM}} = \frac{\|X_{ROM} - X_{FE}\|^2}{\|X_{FE}\|^2}$$

4 parameters



2 parameters – Min Princ Strain



Conclusions

- Complex ROMs (D, L, θ, φ) hetero/friction: errors lower than 5% for metrics in the screws
- Simplified ROMs homo/bonded useful for metrics in both the screws and the bone
- Further analyses needed to optimize the ROM for the screws-bone frictional case

Prediction of the shape of human lumbar vertebrae from adjacent ones by Singular Values Decomposition

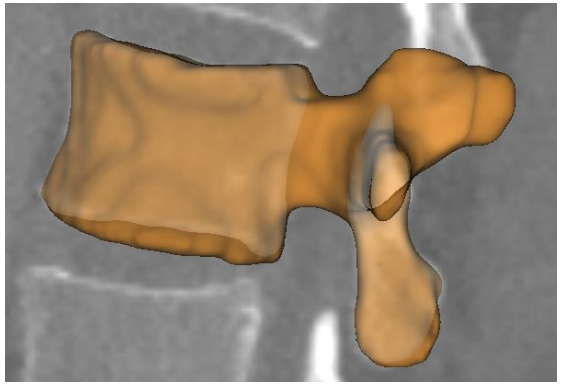
M. Sensale[a,b], T. Vendeuvre[c], A.Germaneau[d], C.Grivot[a], E. Dall'Ara[b], M. Rochette[a]

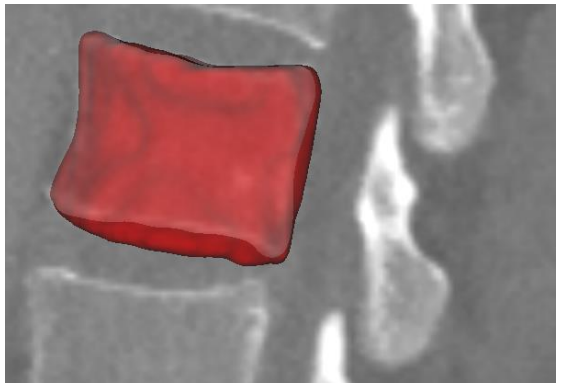
[a]ANSYS, France; [b]University of Sheffield, UK; [c]Poitiers University Hospital, France; [d]University of Poitiers, France

Presented at ISB 2021 conference, Stockolm, July 2021

Vertebral body segmentation + Mesh registration

- 40 patients (22 men, 18 women)
- 40.9 ± 15.9 years
- Manual procedure (3D Slicer)





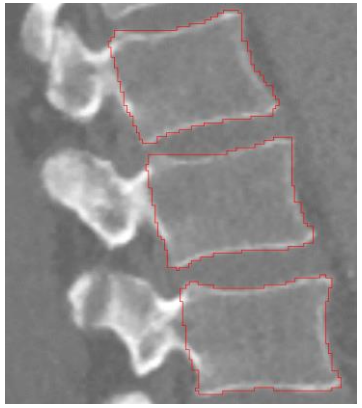
VerSe: Large Scale Vertebrae Segmentation Challenge
https://github.com/anjany/verse [1] [2]

- Template mesh generation
- Semi-automatic procedure
- Mean registration error 0.14 mm

Anatomical landmarks

[1] Löffler et al. 2020 [2] Sekuboyina et al. 2020

Prediction of the shape of L1: least-squares optimization



T12

L1

L2

$\boldsymbol{A}$

$\varphi_1 \ldots \varphi_m$

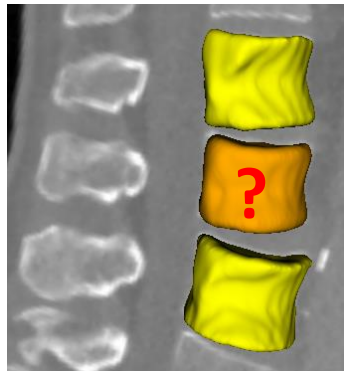
T12	h1 ⋮ h7
L1	h1 ⋮ h7
L2	h1 ⋮ h7

$\boldsymbol{A_{T12-L2}}$

$\boldsymbol{A_{L1}}$

h

T12	h1 ⋮ hJ
L1	?
L2	h1 ⋮ hJ



optimization

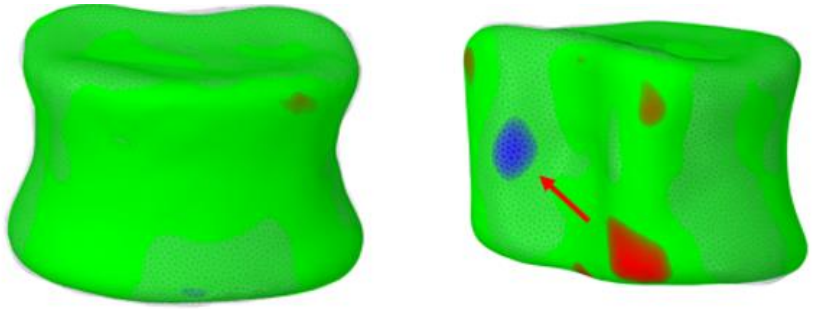
L1 h1 ⋮ hJ

m = 6 modes

Results

Level(s) used	Mean error (mm)		Hausdorff distance (mm)	
	Average ± st dev	(Min, Max)	Average ± st dev	(Min, Max)
T12 and L2	0.51 ± 0.11	(0.29, 0.96)	2.11 ± 0.56	(1.38, 4.52)

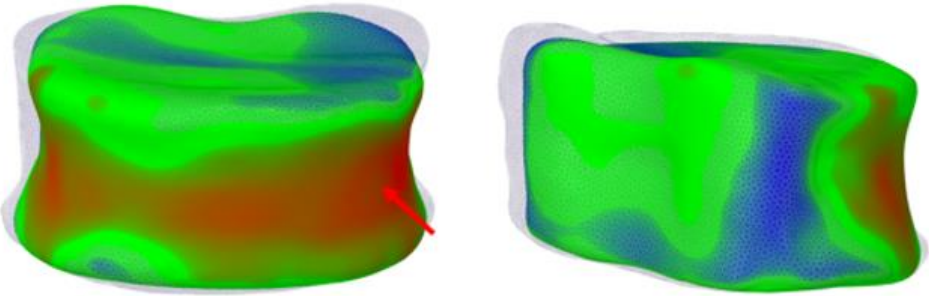
Patient #4



Lowest mean error = 0.29 mm

Hausdorff distance = 1.40 mm

Patient #11

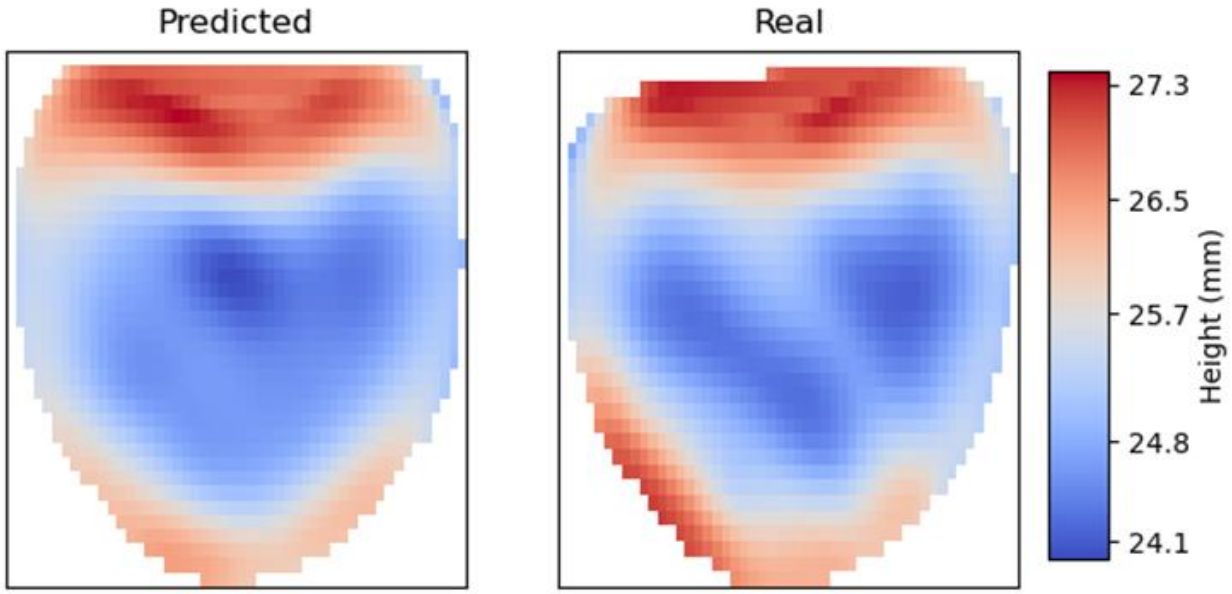


Highest mean error = 0.96 mm

Hausdorff distance = 4.52 mm

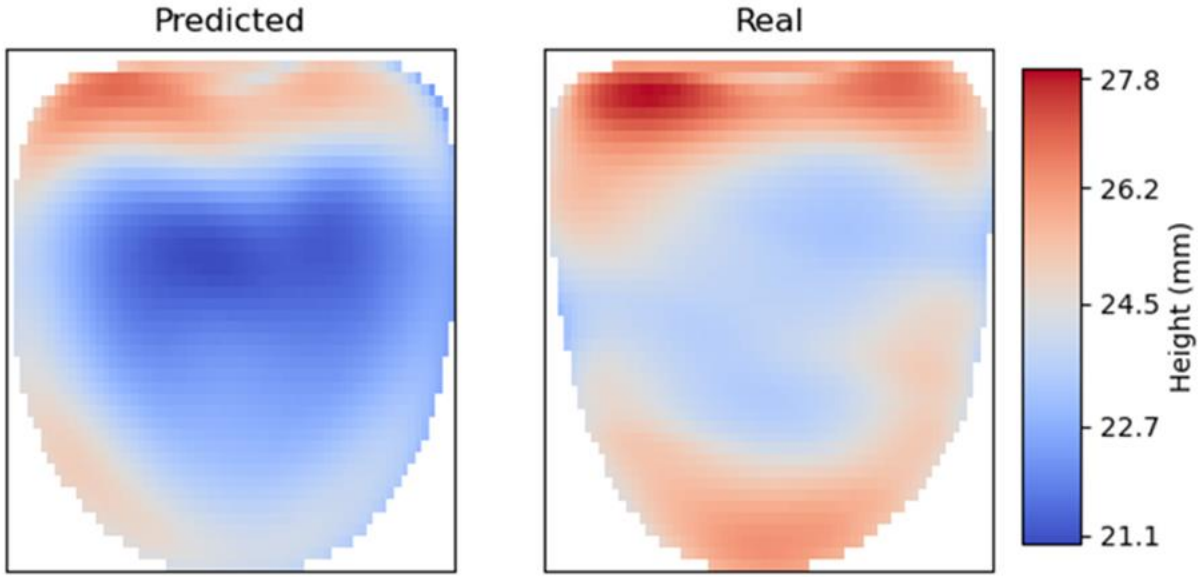
Results

Patient #4 -> mean error 0.29 mm



Best mean error

Patient #11 -> mean error = 0.96 mm



Worst mean error

Conclusions

- Mean reconstruction error lower than 0.6 mm
- Hausdorff distance lower than 2.2 mm (often localized at postero-lateral part of the vertebral body)
- Distribution of heights accurately estimated

Summary

- Element size: 0.6 mm (screws) and 1.0 mm (bone) ➔ relative differences ≤ 5%
- Diameter more important than length of screws
- ROMs of complex FE (D, L, θ, φ) hetero/friction ➔ metrics in the screws
- ROMs of FE homo/bonded ➔ metrics in the screws & in the bone
- Prediction L1 pre-fracture shape ➔ mean error lower than 0.6 mm

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Christelle Grivot
Wenfeng Ye

Tanguy Vendeuvre

Marco Biancolini

Cameron James
Chloé Techens
Denata Syla
Jennifer Fayad
Jose Rodrigues

Thank you!