Department of Mechanical Engineering

Human femur fracture: experimental and numerical analysis

Miguel Marco[1], Adrián Arias-Blanco[1], José Ramón Caeiro[2], Ricardo Larraínzar[3], Eugenio Giner[4], María Henar Miguélez[1]

1 Department of Mechanical Engineering, Universidad Carlos III de Madrid
2 Department of Mechanical and Materials Engineering, Universitat Politècnica de València
3 Orthopedic Surgery and Traumatology Service, Complejo Hospitalario Universitario de Santiago de Compostela,
4 Orthopaedics and Trauma Department, Surgery Department, Hospital Universitario Infanta Leonor

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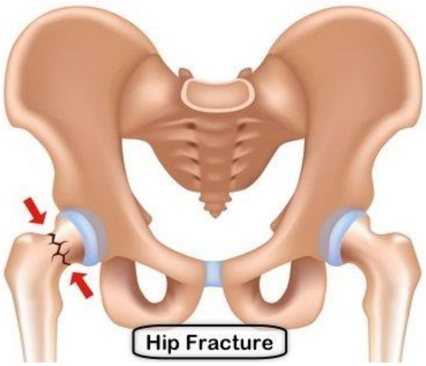
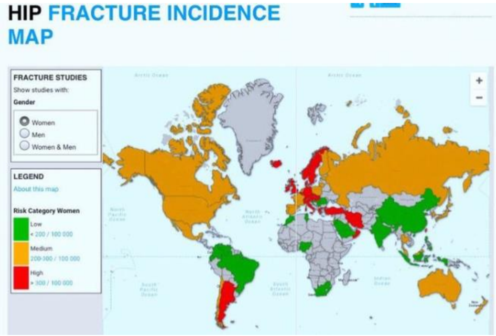
Introduction

- Hip fracture
  - **Very common disease** (1.6 million worldwide in 2000)
  - In-hospital mortality (22% men and 14% women)
  - **Surgical revision** needed in 12% of patients
  - Twice as many fractures in 2050 compared to 2018 *[Cheung 2022]*



- Some parameters in Spain
  - **40.000-50.000** fractures per year (2012)
  - 75% of patients → **women**
  - **Social cost**: 8.365 € per patient, nearly 1.591 M€



Global Women's Health Initiative, 2019

Introduction

- <u>**General objective**</u>

  Analyse the mechanical behaviour of the **human femur** (experimentally and numerically)

- <u>**Partial goals**</u>

  - Predict **femur fracture morphology** in different individuals (**patient-specific** philosophy)

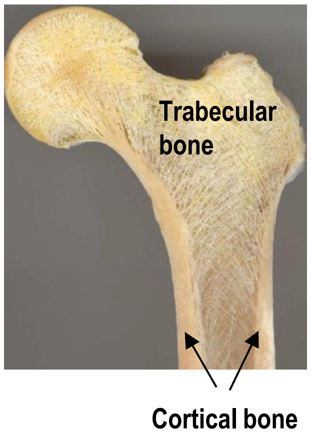
    - Analyse femur-related data to explain fracture morphology

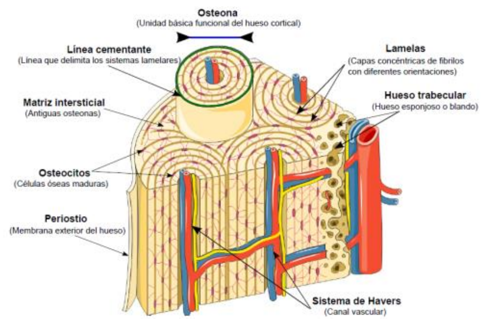
  - Use experimental and numerical methods in a **common clinical problem**: the **cut-out phenomenon**

Introduction

Cracks in bone tissue

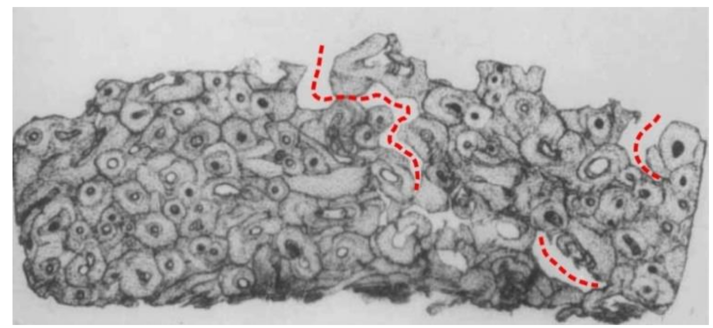
- Microscopic scale (cortical bone)





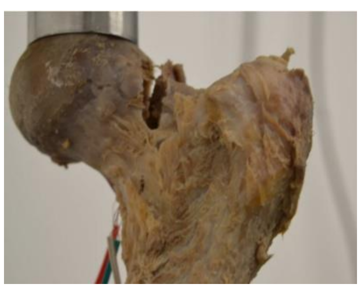
Cortical bone structure

- Crack propagation through **cement lines**
- **Non-precise prediction** in other works



[Evans, 1976]

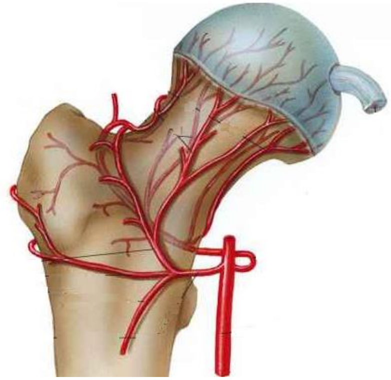
- Macroscopic scale (human femur)



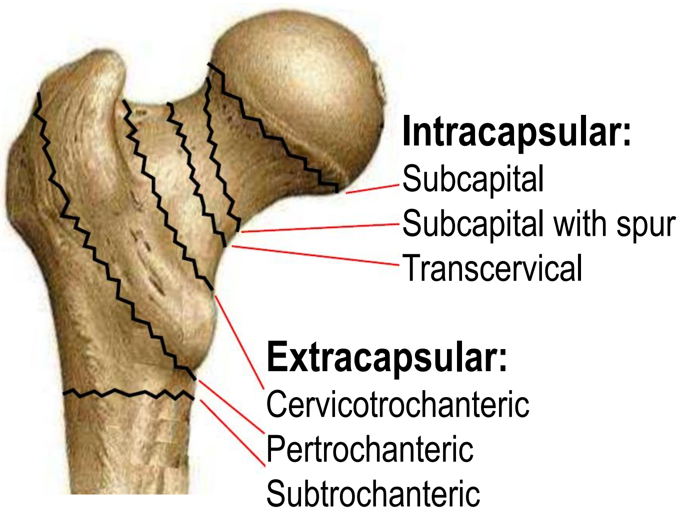
- **Differences in fracture morphology** under similar conditions
- Importance of the type of fracture: different **surgery and treatment**
- ***Patient-specific***

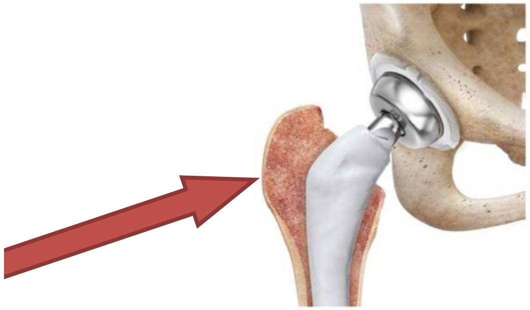
Introduction

- Types of fractures and their treatments:
  - Intracapsular → whole femoral head prosthesis
  - Extracapsular → union with intramedullary nail

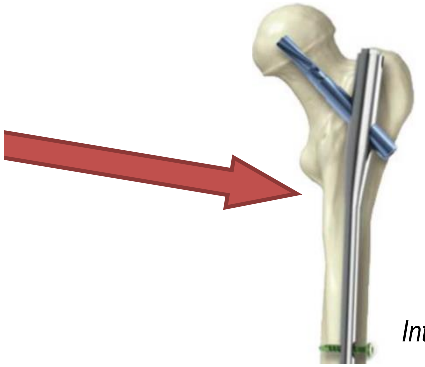


Bloody supply in the femur





Hip prosthesis

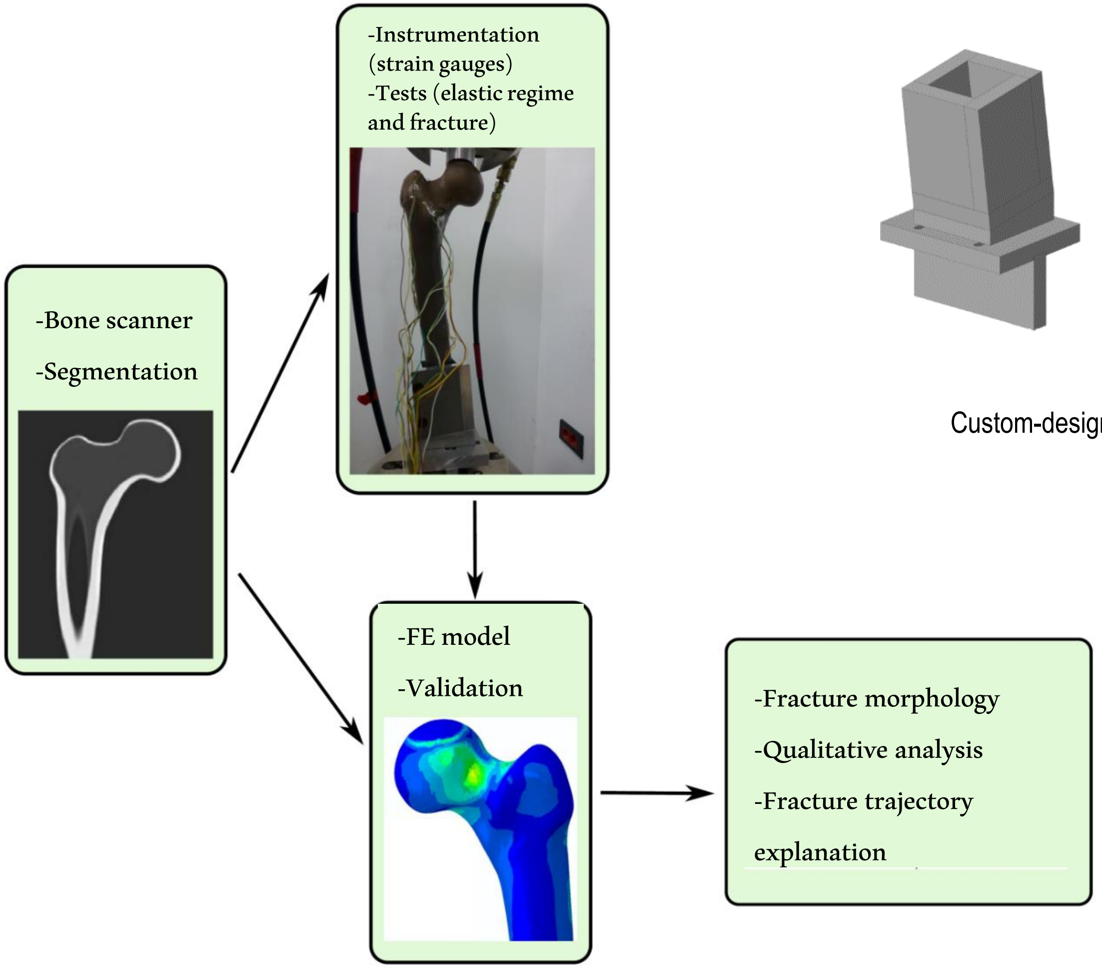


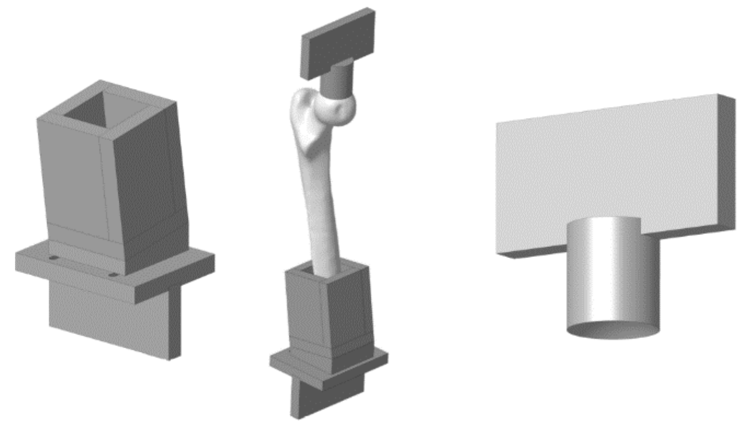
Intramedullary nail

Contents

Experimental work

- Methodology





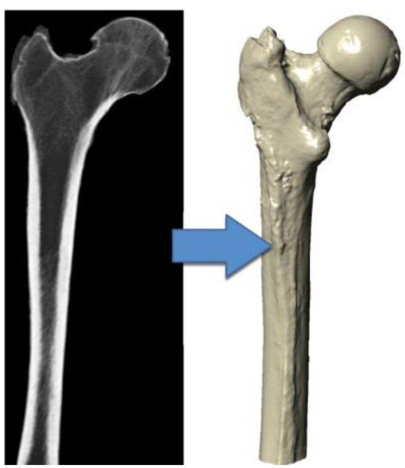
Custom-designed rig for the experimental tests

Experimental work

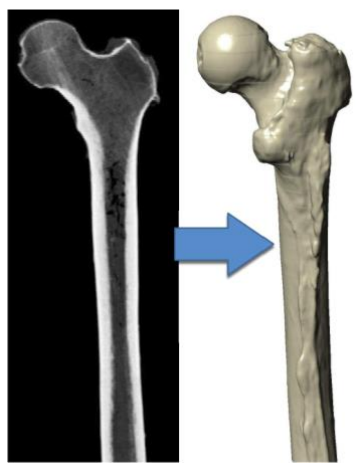
- Donor anthropometric data

Specimen	Side	Sex	Age	Height (cm)	Weight (kg)
# 1	Left	Woman	72	158	78
# 2	Right	Man	73	170	88

- Scan and geometry acquisition



Specimen 1

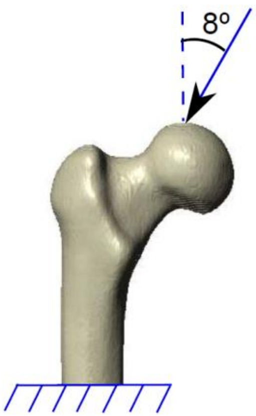


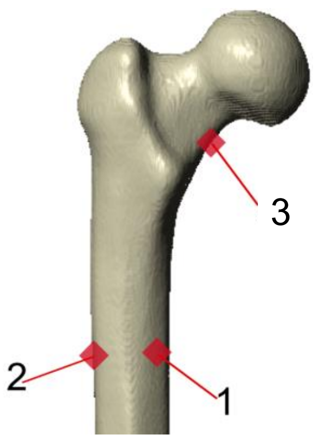
Specimen 2

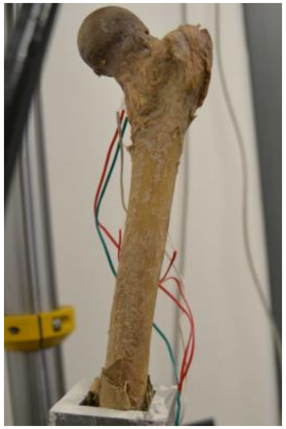
- Through Computed Tomography (CT)
- Resolution: $0.2 \times 0.2 \times 0.2$ mm^3
- Material distinction via Hounsfield Units

Mechanical tests

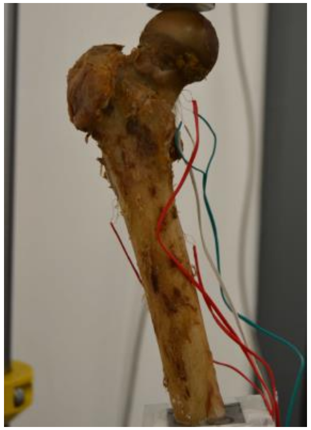
- Elastic regime tests







Specimen 1

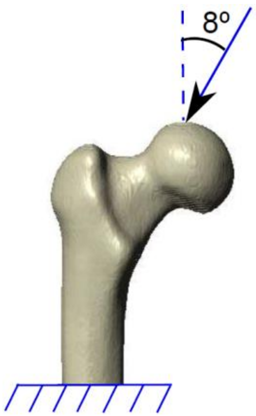


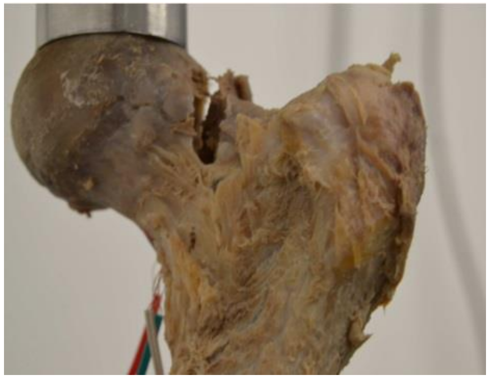
Specimen 2

- 4 loads: 500 N, 1000 N, 1500 N and 2000 N
- 2 uniaxial strain gauges (1 y 2)
- 1 rosette gauge (3)
- 32 measurements points

Mechanical tests

- Fracture tests





Specimen 1

- F_{max} = 6010 N
- **Intracapsular**
- Femoral head prosthesis

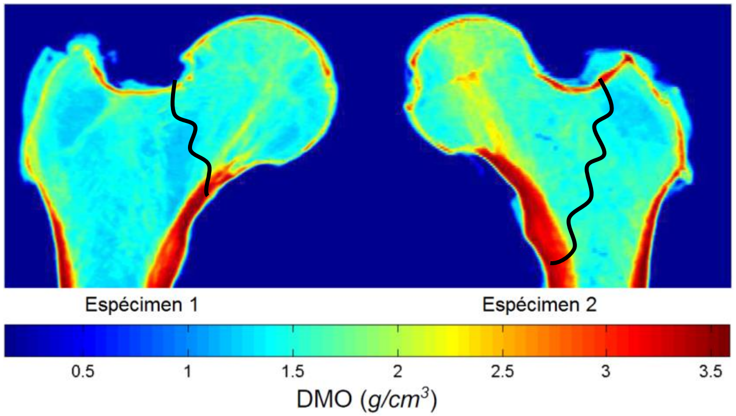
Specimen 2

- F_{max} = 7120 N
- **Extracapsular**
- Intramedullary nail

***Patient-specific** treatment*

Qualitative analysis of specimens

- Global Bone Mineral Density (BMD) analysis



- Greater cortical thickness in specimen 2
- Higher trabecular density in specimen 2
- Weakened neck in specimen 1
- Reinforced neck in specimen 2

- Relative parameters to BMD

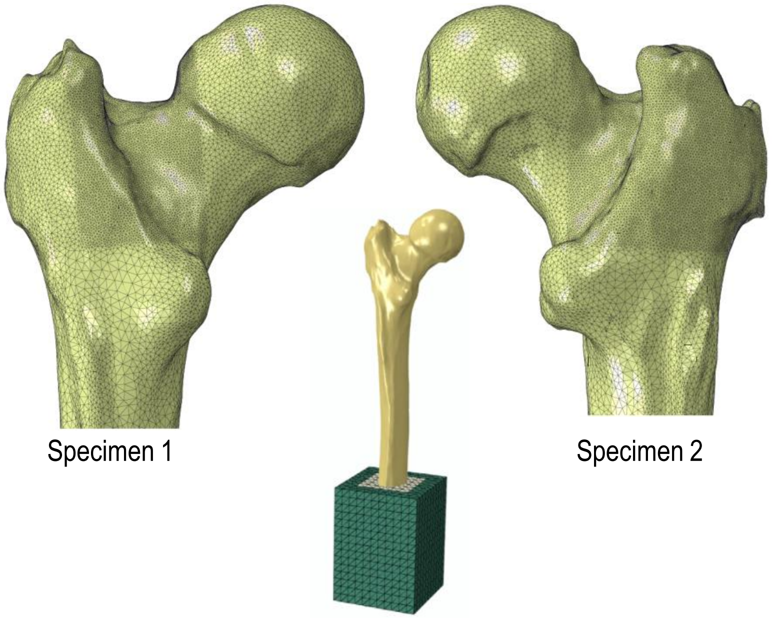
Parameter	Specimen 1	Specimen 2
% trabecular	76.5	66.0
% cortical	23.5	34.0
$\rho_{trab,aver}$ (g/cm3)	1.49	1.54
$\rho_{cort,aver}$ (g/cm3)	2.46	2.54

- Lower cortical percentage in specimen 1
- Lower trabecular and cortical density in specimen 1

Contents

Numerical models

- Model characteristics
  - Mesh
    - C3D10 elements
    - Diaphysis → 3 mm
    - Proximal zone → 2 mm
    - Fracture zone → 1 mm
    - ~$0.5 \cdot 10^6$ elements
    - ~$1 \cdot 10^6$ nodes



- Materials properties dependents on BMD
  - Relationship $\rho \rightarrow E$ (**15 materials**)

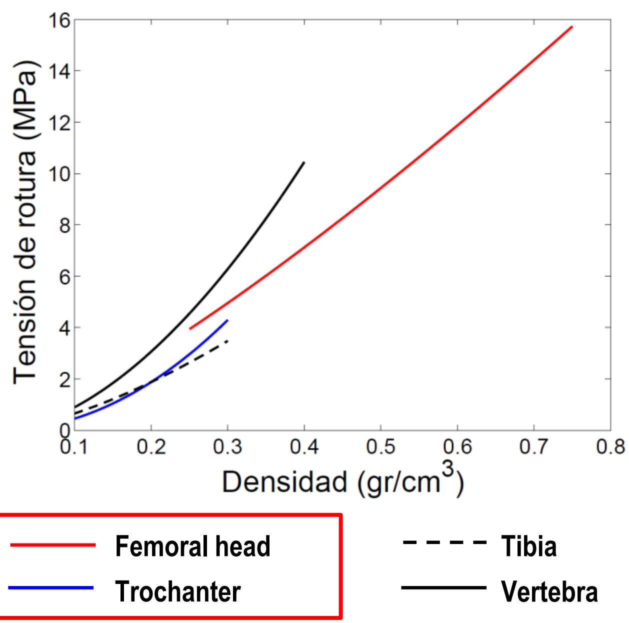
$$\rho(\mathrm{g/cm^3}) = 0.1259 + 1.1563 \cdot 10^{-3}\mathrm{HU}$$

$$E(\mathrm{MPa}) = 6850 \cdot \rho^{1.49}$$

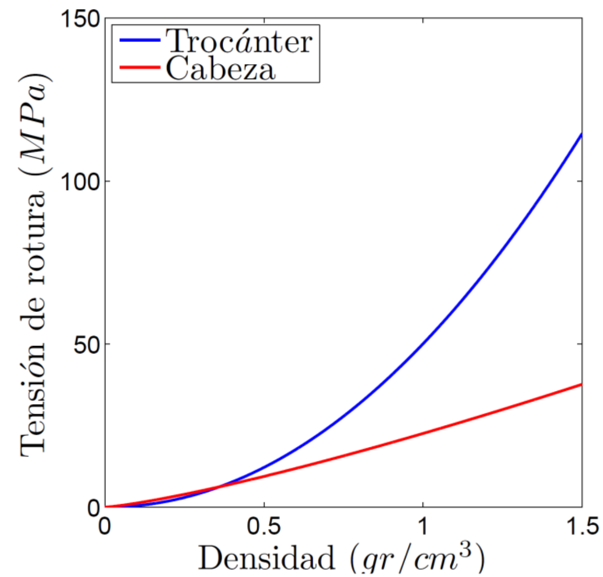
	Specimen 1	Specimen 2
ρ (g/cm^3)	0.20 – 2.44	0.21 – 2.47
E (MPa)	650 - 25953	651 - 26304
v	0.3	0.3

Fracture modelling

- Strength limits as a function of **BMD *(patient-specific)***
  - Common use of homogeneous criteria
  - Implementation of heterogeneous damage
    - Via USDFLD subroutine ($\boldsymbol{f = \sigma_{max,ppal} / \sigma_{ult}}$)
      - Stiffness degradation of elements
      - Automated successive analysis



[Morgan and Keaveny, 2001]



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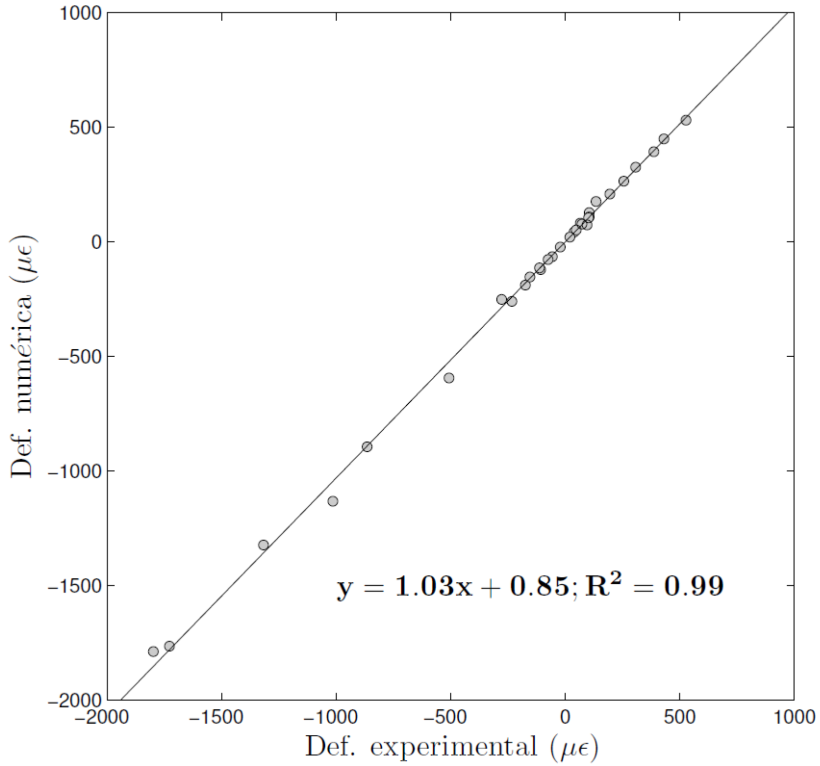
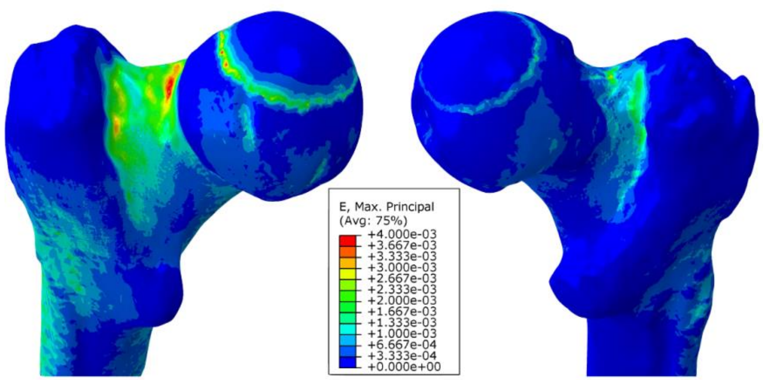
Elastic regime



- Relative error = **6%**
- Maximum strains located in the **upper neck region**
- **Early indicators** of final fracture morphology

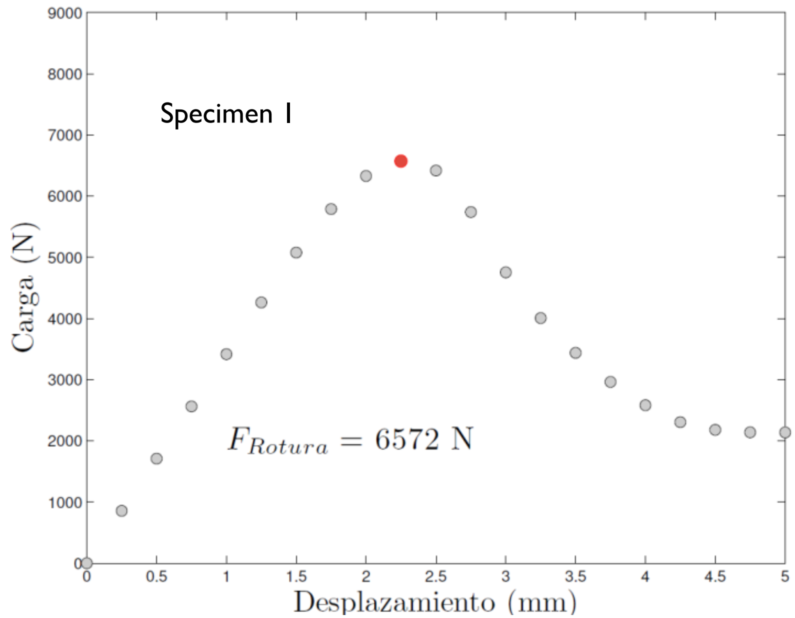


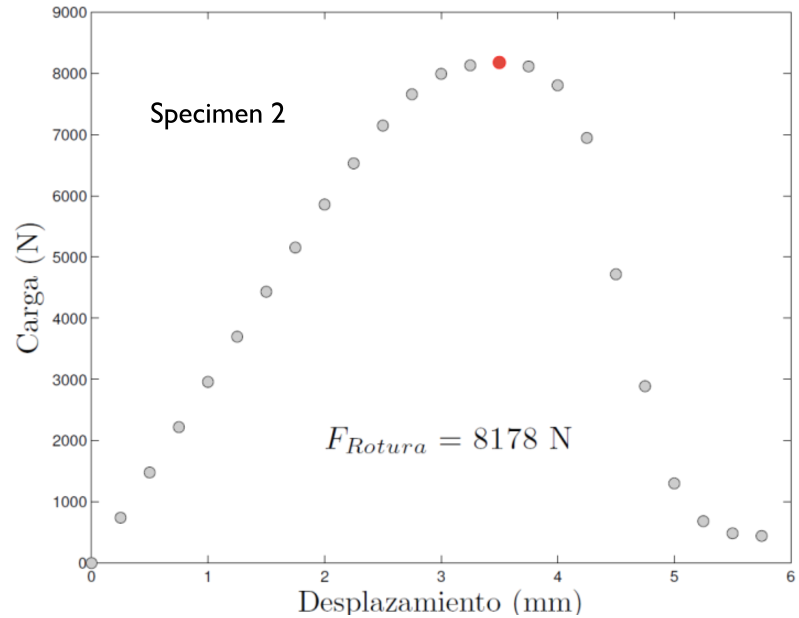
Specimen 1

Specimen 2

Maximum load

- Analysis of **force-displacement curve**





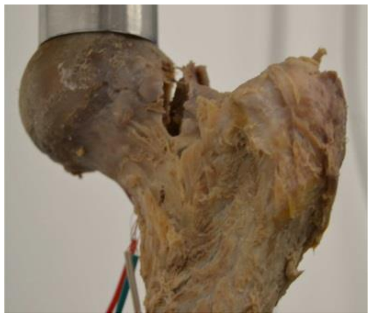
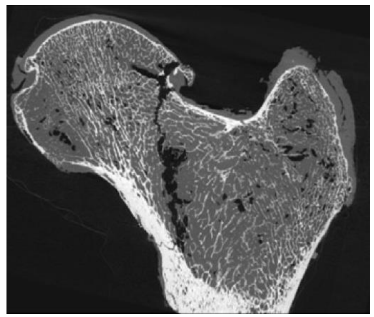
Specimen	Exp. (N)	Num. (N)
#1	6010	6572
#2	7120	8178

Relative errors of **9%** and **15%**

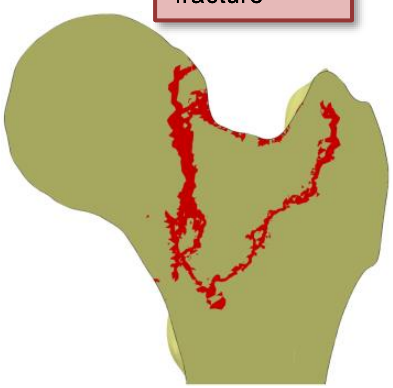
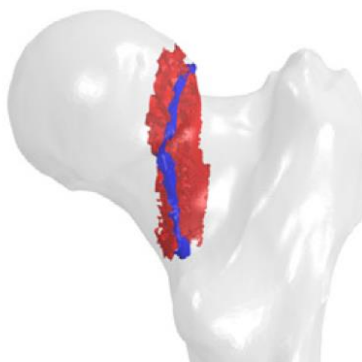
Fracture morphology, comparison

- Comparison between experimental and numerical fracture path

Specimen 1

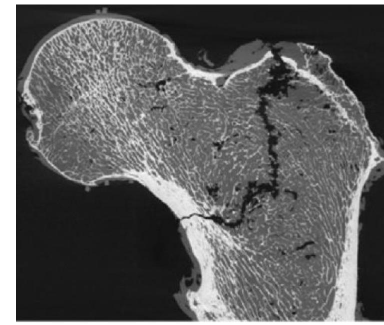



Intracapsular fracture

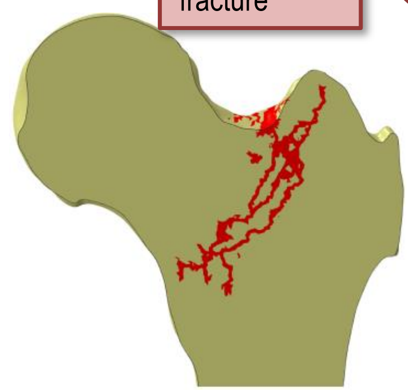
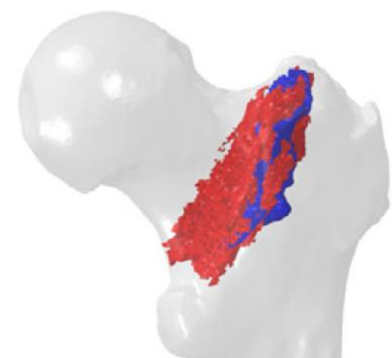



Numerical
Experimental (from micro-CT)

Specimen 2

Extracapsular fracture

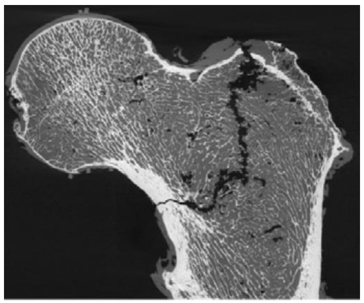



Numerical
Experimental (from micro-CT)

Contents

Application to cut-out phenomenon

- *Cut-out phenomenon:* collapse of the intramedullary nail-femur structure

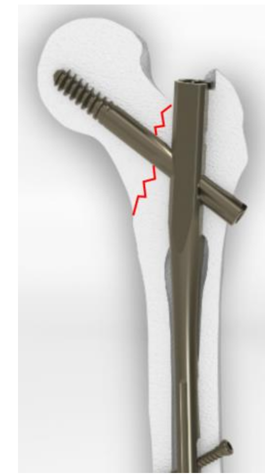


Extracapsular fracture

Extracapsular fracture Fixed with intramedullary nail

Cut-out phenomenon

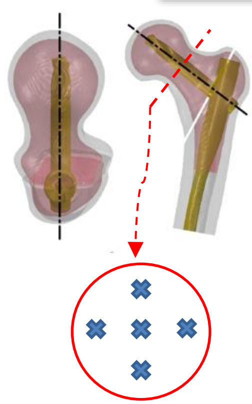
- Gaps and rotations
- Incidence: 5 – 12%
- Need of revision surgery
- Influence of nail-femoral neck position?
- Most studies are clinical or experimental

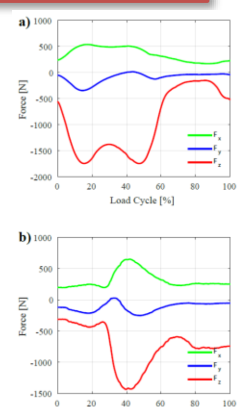


- Methodology

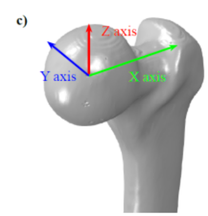
Experimental tests

Numerical models





Walking and standing up

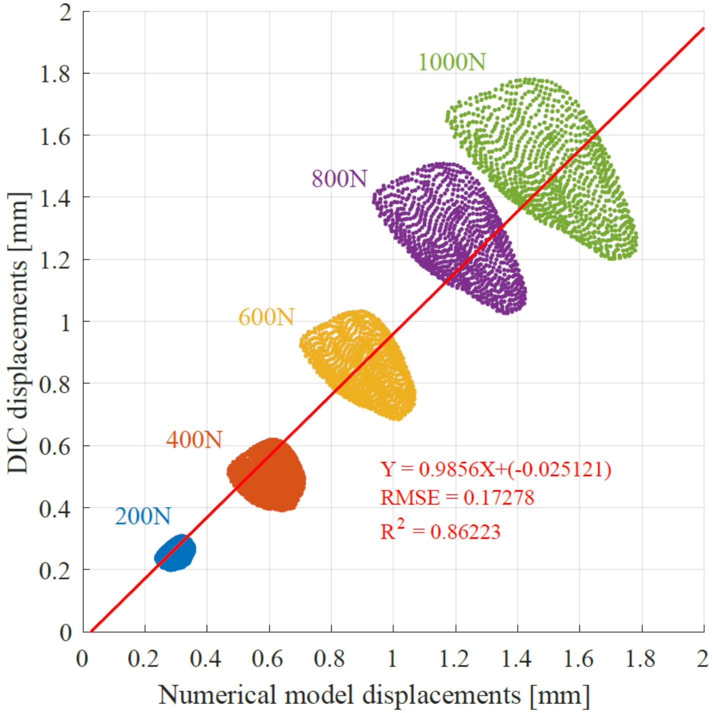


Left femoral head seen frontwards

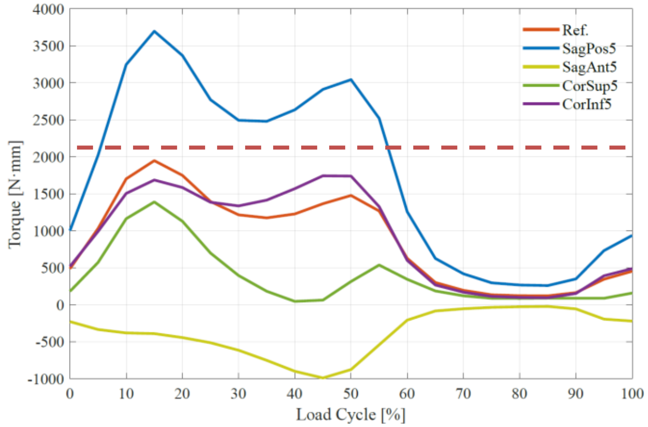
- Variation of positions
  - Sagittal plane: ±5 mm
  - Coronal plane: ±5 mm
- Results to analyze
  - Displacements in the femur
  - Torque in the nail
  - Damage in trabecular bone

Results

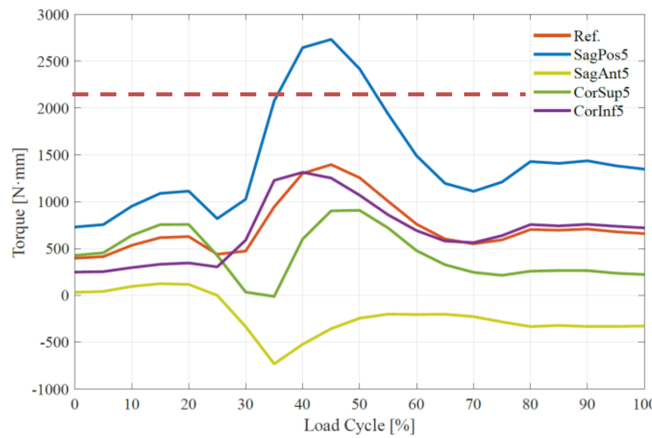
- Validation of the numerical model



- Torque



Walking

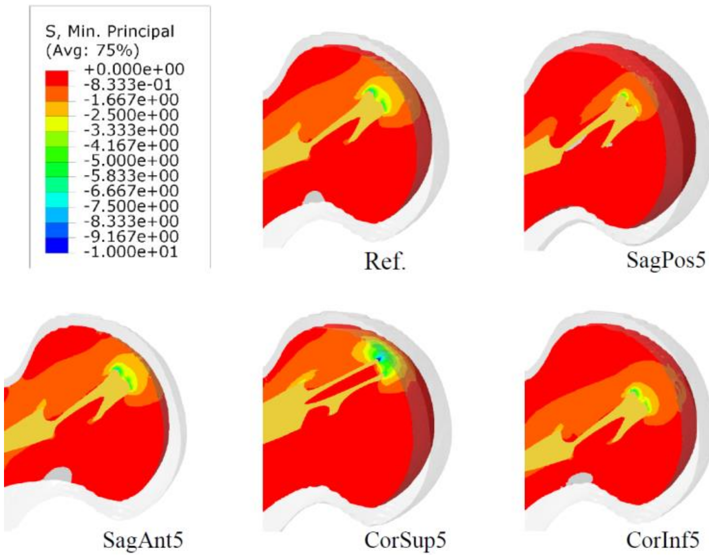


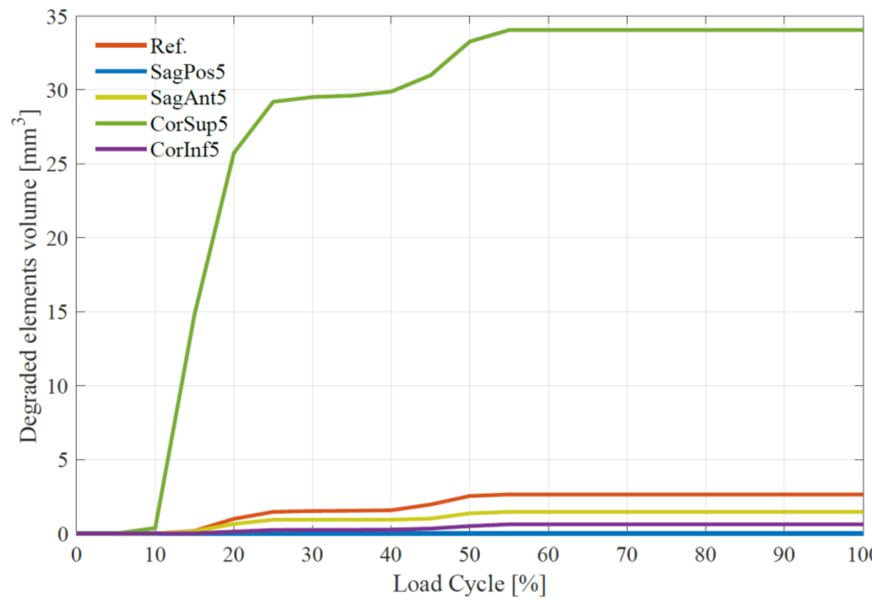
Standing up

Critical torque according to literature

Results

- Damage in trabecular bone





Damaged volume of elements after one load cycle (walking)

Contents

Conclusions

- Satisfactory combination of experimental tests and numerical models
- Numerical models are able to predict different femur fracture trajectories → Different surgical treatment
- Fracture path and mechanical behaviour related to the mechanical state of the femur
- Cut-out phenomenon: numerical models help to optimize the intramedullary nail position: torque and trabecular bone damage

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4 Orthopaedics and Trauma Department, Surgery Department, Hospital Universitario Infanta Leonor

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