Biomechanical devices for bone tissue synthesis and regeneration

PhD Course in **Ingegneria**
XL° cycle

Academic Year **2024/2025**

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Rationale and objective

Why bone regeneration is still a challenge

- **critical-size** bone defects exceed the body's healing capacity
- bone repair requires both **mechanical** stability and a favorable **biological** environment

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Objective: to investigate mechanical and biological strategies for bone regeneration, with a focus on their potential complementarity

Rationale and objective

Objective: to investigate mechanical and biological strategies for bone regeneration, with a focus on their potential complementarity

Additive Manufacturing

- complex geometries and patient-specific implants
- lattice structures → trabecular bone porosity and stiffness
- widely used Ti6Al4V alloy
- numerical validation

Regenerative Medicine

- regeneration depends on local biological environment
- biomaterials + cells + biochemical cues
- hydrogels mimicking ECM
- collagen and GelMA

FDM gyroid PEKK lattices

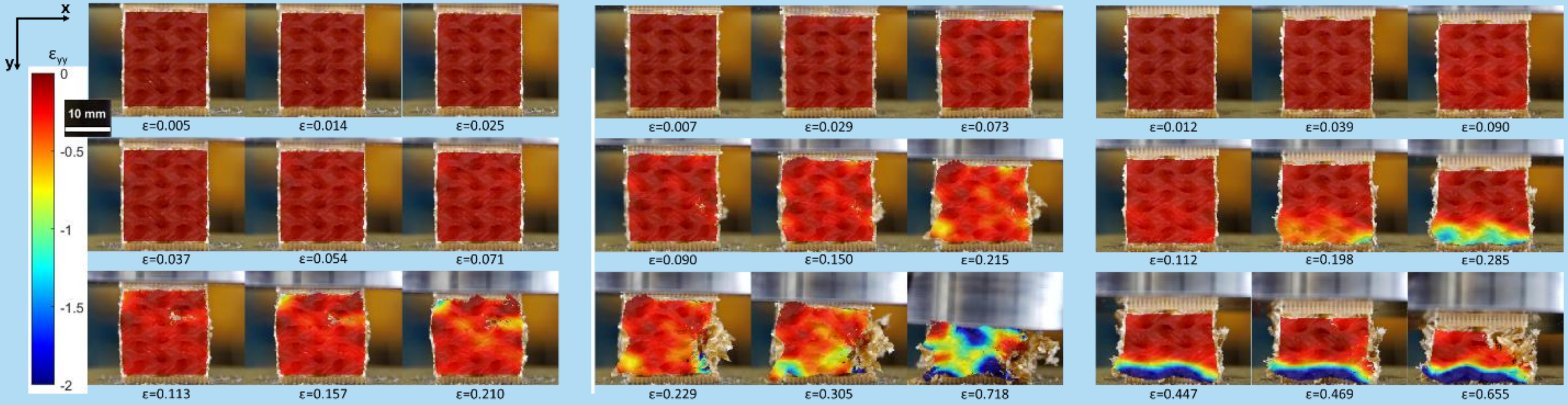
Mechanical characterization for orthopedic applications

PEKK
- mechanical properties ~ bone
- imaging compatibility
- more suitable for AM

TPMS gyroid structure
- interconnected **porosity**
- surface area for cell attachment (**osseointegration**)
- mechanical tuning through **relative density**

Compression tests

- 300 N **pre-load** and up to large deformations to study onset and **evolution of collapse**
- full-field deformation analysis through Digital Image Correlation (**DIC**)



0.2 mm/min
- constant deformation
- no macroscopic fracture zones

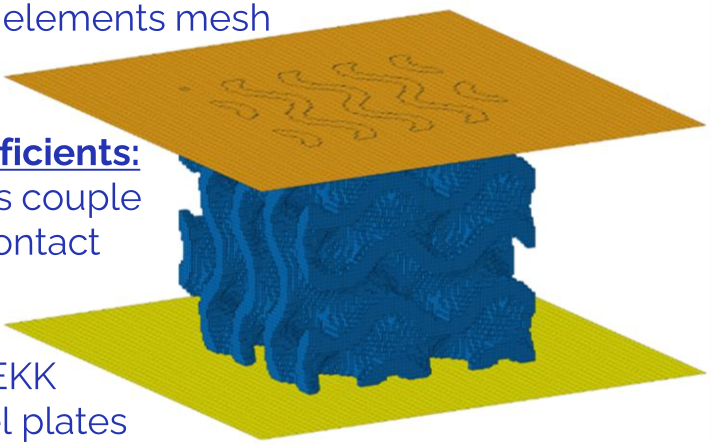
2 mm/min
- earlier cell collapse
- diagonal shear bands
  → bending-dominated

20 mm/min
- deformation in lower layers
- brittle-like collapse
- higher measured peak forces

FDM gyroid PEKK lattices

Numerical modelling and FEM validation for 20 mm/min

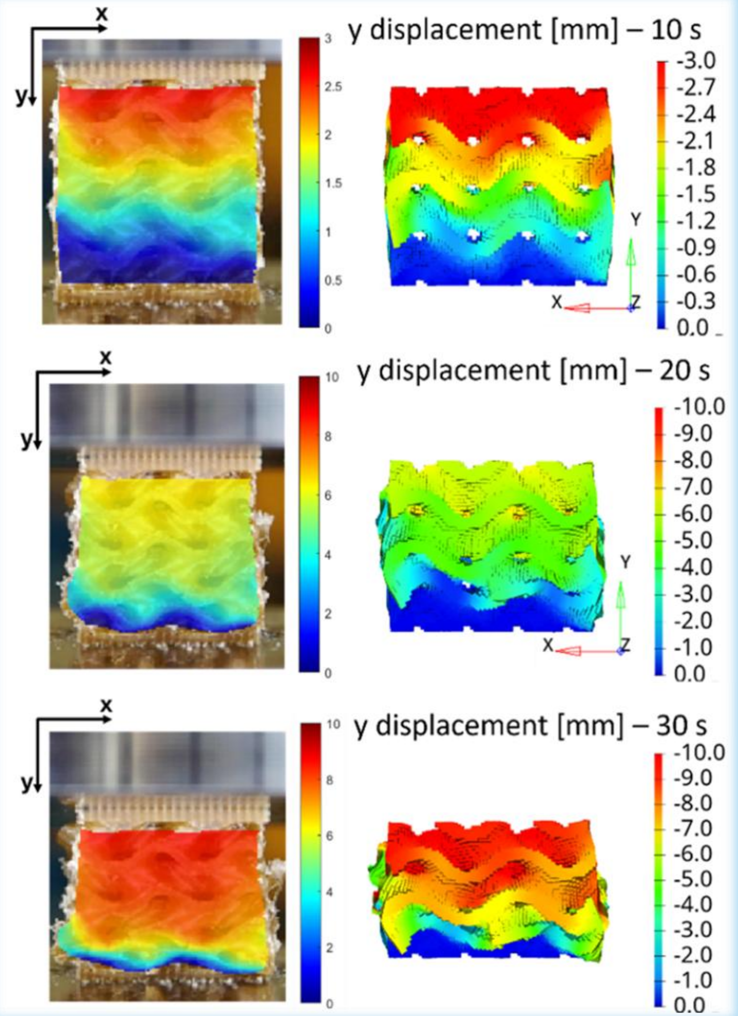
- **HyperMesh:**
  - gyroid lattice → 0.6 mm hexahedral mesh
  - plates → 1 mm quad elements mesh



- **Contacts friction coefficients:**
  - 0.50 for lattice–plates couple
  - 0.45 for lattice self-contact
- **Material laws:**
  - Johnson–Cook for PEKK
  - linear-elastic for steel plates

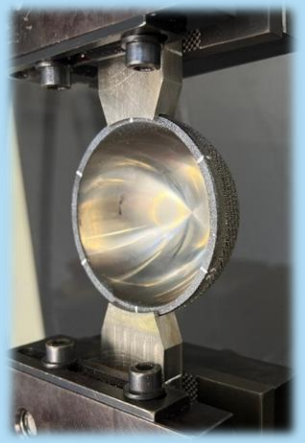
	E [GPa]	ν	P [kg/m3]	σ_{MAX} [MPa]	ε_f	ε_{dam}
PEKK	2.3	0.4	1280	64	0.3127	0.2536
Steel plates	210	0.3	7850	/	/	/

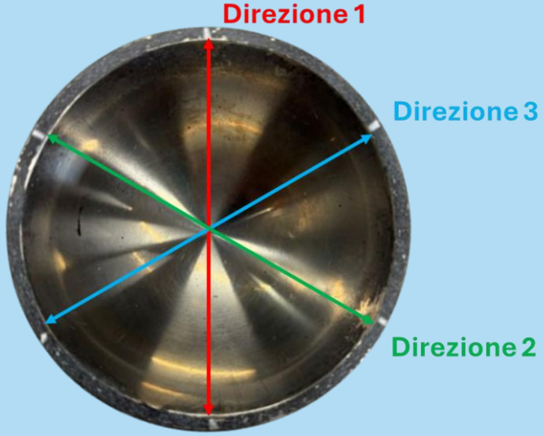
Validated FEM model as a foundation for future design of PEKK-based porous orthopedic devices



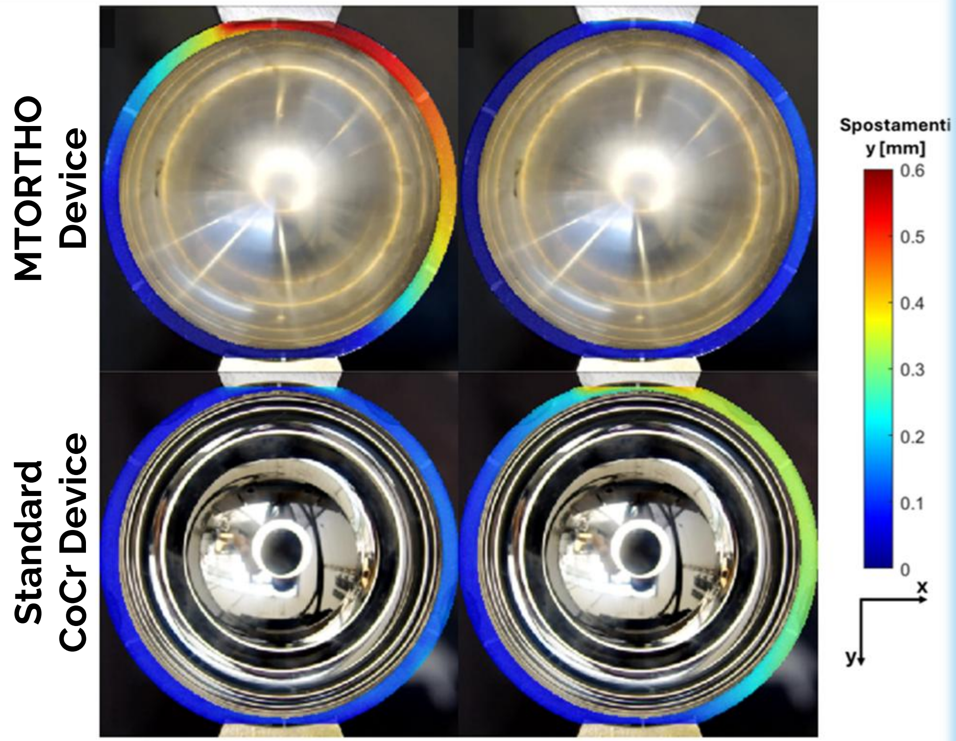
Tests on acetabular cups

Short-term deformation under diametral compression





- press-fit acetabular shells
- Ti6Al4V ELI alloy by EBM
- external porous region with rhombic dodecahedral lattice (3 mm unit cell)



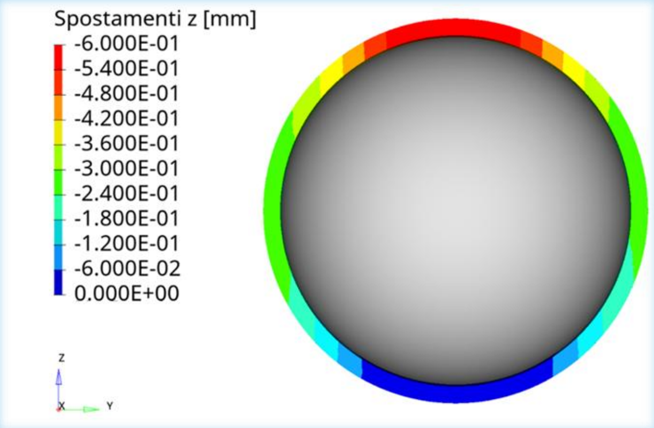
Tests

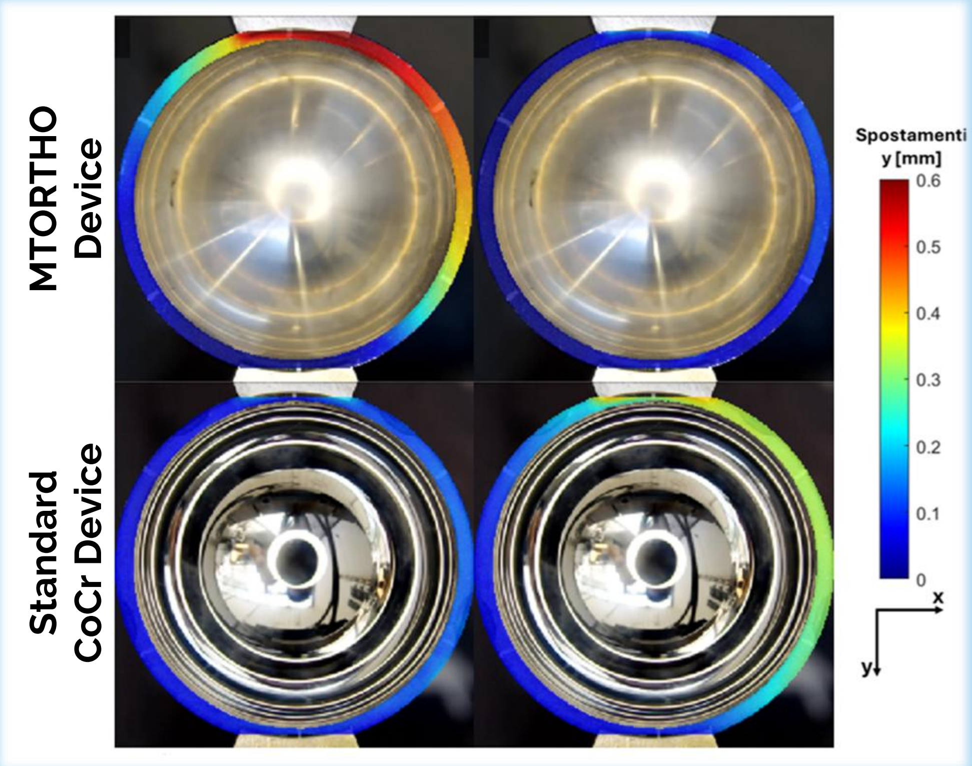
- 1000 N diametrical two-point compressive load (120° rotation)
- internal diameter measurements before, during and after loading

Introduction of porosity did not compromise short-term mechanical integrity of the implant

Tests on acetabular cups

Numerical modelling and FEM validation





- 0.5 mm CTETRA first order elements
- equivalent isotropic material for net
- linear static

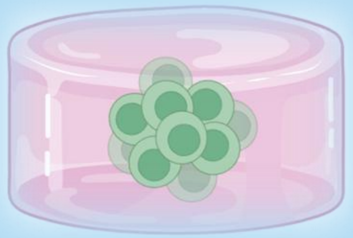
	E [GPa]	ν	σ_{MAX} [MPa]	σ_y [MPa]
Ti6Al4V (melt)	108	0.3	965	873
RD 3 mm (net)	0.224	0.3	11.1	/

→ Validated FEM model for further parametric analyses on implant geometry and thickness

Immunomodulatory hydrogels

for bone tissue regeneration

- Bone healing is regulated by **immune** and **inflammatory processes**
- Excessive or **prolonged inflammation** impairs regeneration
- Timely immune regulation promotes **osteogenesis** and vascularization



Immunomodulatory cell-based strategies

Role of hydrogels

- enable localized delivery of therapeutic cells
- create immunomodulatory niches at the defect site

Regulatory T cells (Tregs)

- control excessive immune responses
- support tissue repair and immune homeostasis

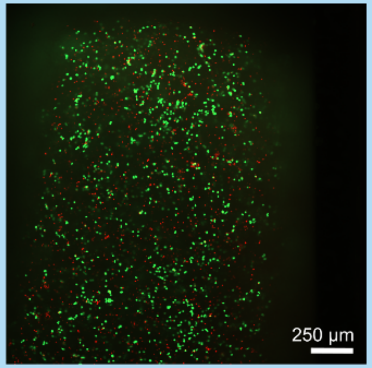
Immunomodulatory hydrogels
for bone tissue regeneration

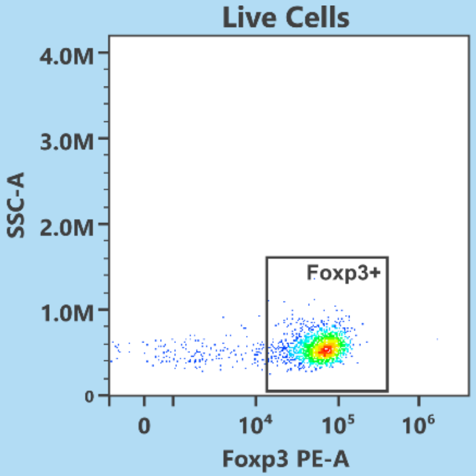
Protocol and analysis:

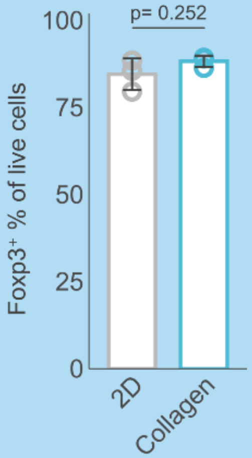
1) CD4+ T cells isolation from mice spleens
2) Differentiation into Tregs with IL-2 and TGF-β for 4 days
3) Encapsulation in Collagen and GelMA hydrogels (500,000 cells/gel)
4) Live/Dead staining and flow cytometry for Foxp3 expression after 2 days

Results:

- High cell **viability**
- Homogeneous **distribution** of cells
- Preserved **Foxp3** expression after encapsulation







→ ***Toward GelMA hydrogels***
Collagen: excellent bioactivity but fast degradation
GelMA: tunable stiffness, degradation, and stability

Thanks for your attention