A Novel Planning Paradigm for Augmentation of Osteoporotic Femora

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BIGSS
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LABORATORY FOR
Computational
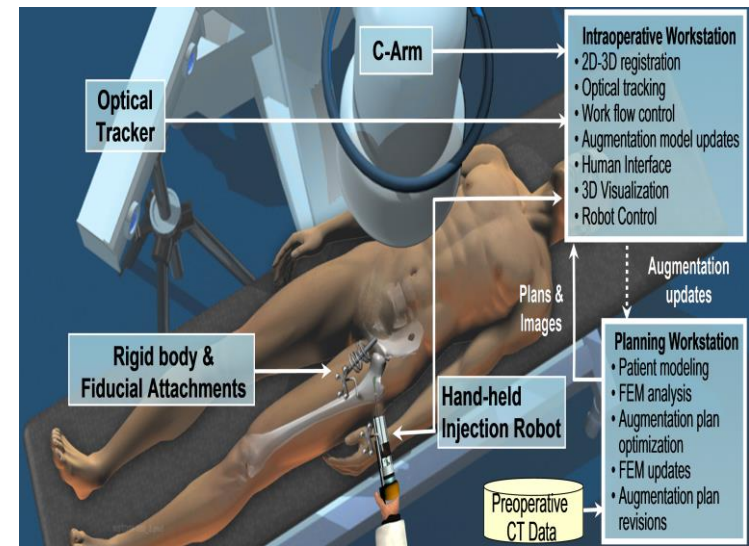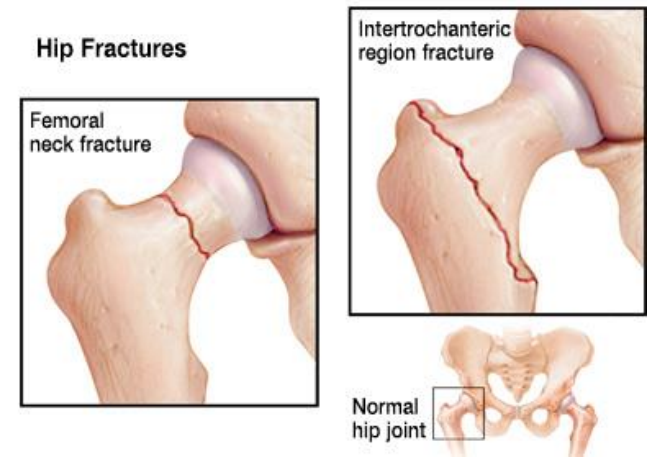Sensing + Robotics
THE JOHNS HOPKINS UNIVERSITY

Overview of Project Goal

Common Problem for elderly:

- Osteoporotic bone fractures

Goals:

- Address the potential risk of thermal necrosis associated with femoroplasty

- Thermal necrosis in tissues exposed to temperatures above 50° C for more than 1 min

- Measure and evaluate temperature rise of the bone surface after the injection

- Create a thermal Finite Element (FE) model simulating temperature distribution during femoroplasty

Paper Selection

❑ <u>Temperature elevation caused by bone cement polymerization during vertebroplasty</u>

Authors: Deramond, H., N. T. Wright, and Stephen M. Belkoff

Journal of Bone (1999)

❑ <u>Temperature measurement during polymerization of bone cement in percutaneous vertebroplasty: an in vivo study in humans</u>

Authors: Anselmetti, Giovanni Carlo, et al.

Journal of *Cardiovascular and interventional radiology* (2009)

✓ Experimental Studies to measure in vitro and vivo temperatures

❑ <u>Thermal analysis of bone cement polymerisation at the cement–bone interface</u>

Authors: Stańczyk, M., and B. Van Rietbergen.

Journal of biomechanics (2004)

✓ Thermal Finite Element Simulation study to evaluate temperature distribution
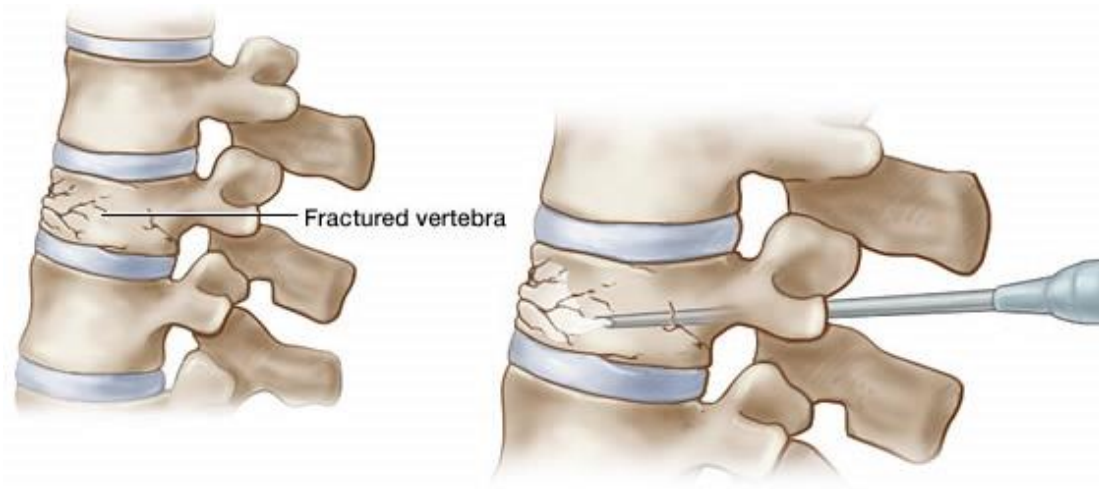
Vertebroplasty

Percutaneous vertebroplasty (PV) treat osteoporotic vertebral compression fracture

Procedure:
- Cement injected in cancellous bone
- Cannula inserted through each pedicle

Complication:
- Thermal necrosis of neural tissue by the heat generated during exothermic polymerization


Fractured vertebra

Significance and Key Results

❑ Experimental Studies to measure in vitro and vivo temperatures:

✓ Thermal necrosis of neural tissue→ Studying thermal effects associated with PVP plays an important role in clinical development of PVP

✓ No thermal damage to spinal cord and nerve roots

✓ Longer dwell time for the medial and anterior parts of vertebral body

✓ Critical items:
- Injected volume of cement
- Concentration of the cement

Experiment Setup → In Vitro

➤ Three spines from elderly females cadavers with vertebral levels T11-T12 and L1-L2

➤ Two different bone cements injected in each pair

➤ Temperatures measured in a bath of saline (37° C), for 15 minutes after the injection

➤ Two 10-gauge needles with three 30-gauge, butt welded, T-type thermocouples along midline of the vertebral bodies

➤ 10cc of bone cement total, 5cc through each needle
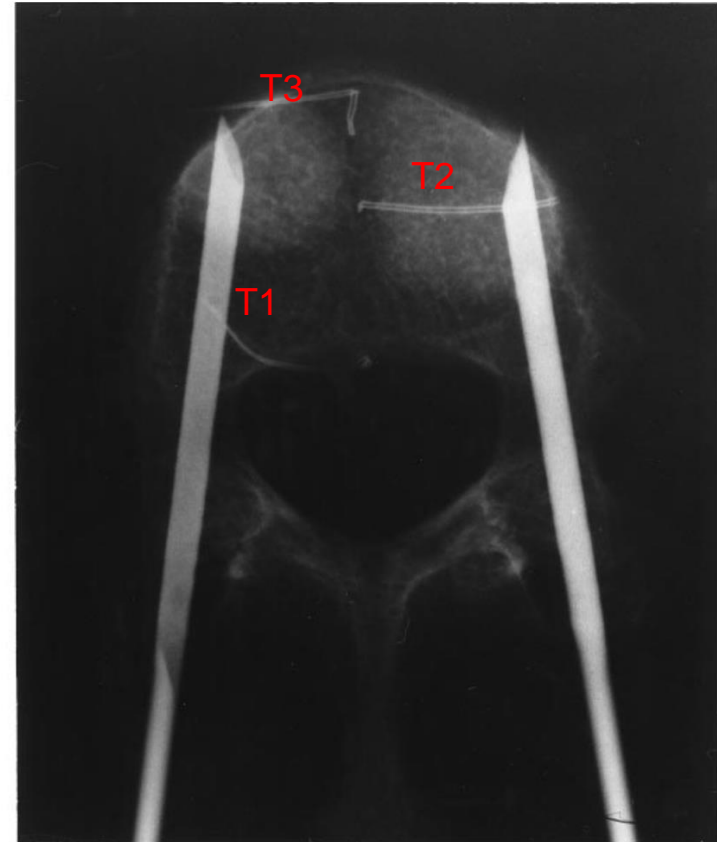
- 22 women with mean age of 75 years suffering from osteoporotic vertebral collapse

- 11 different bone cements, each injected into two patients

- Two 10-gauge needles with 16-gauge radiofrequency (RFA) needle with five thermocouples

- 3 ml of bone cement injected in each vertebral levels L1, L2, L3, L4

- Temperatures recorded every 30 seconds until dropped below 45° C
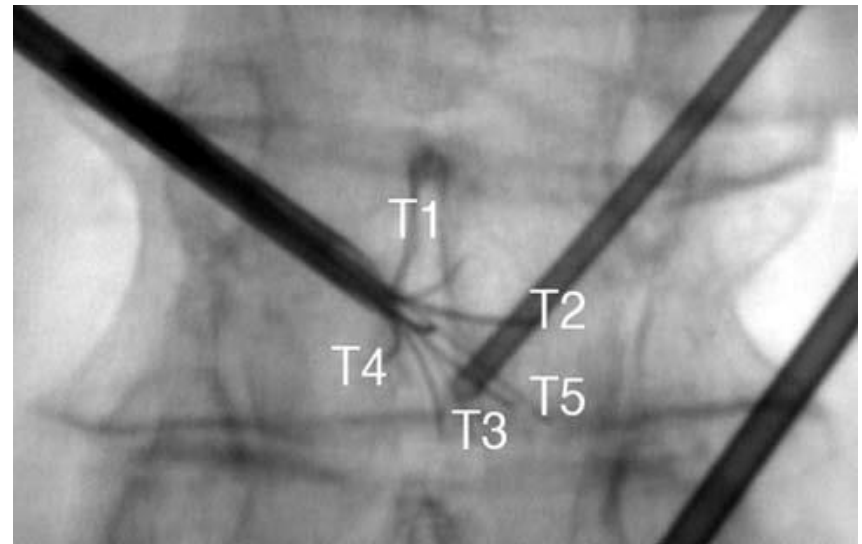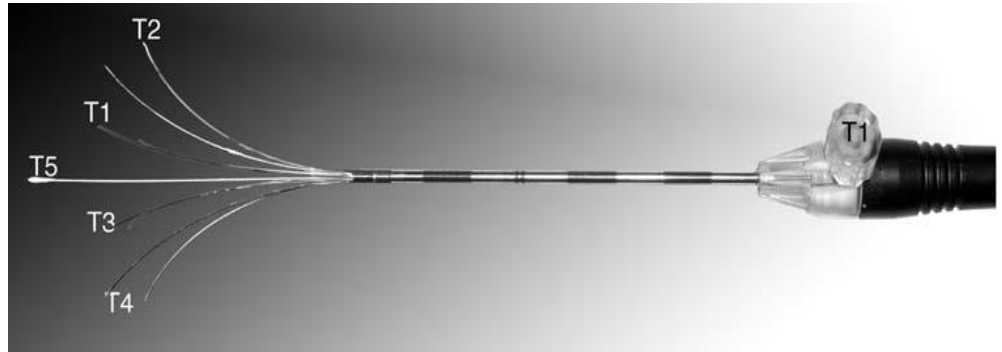
Experiment Results
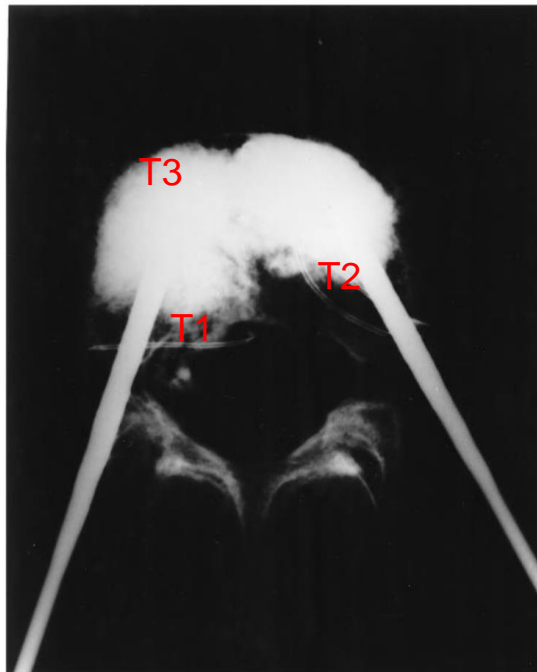
Vitro
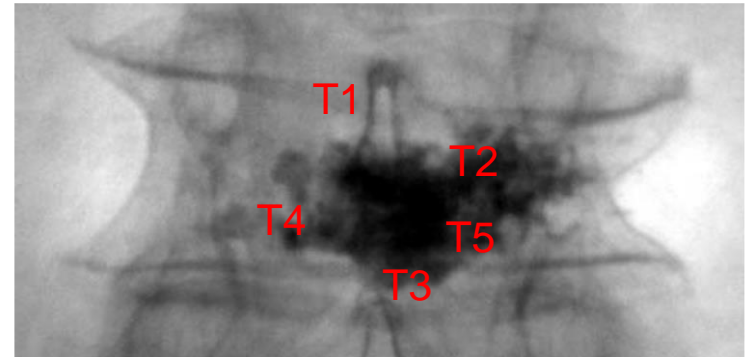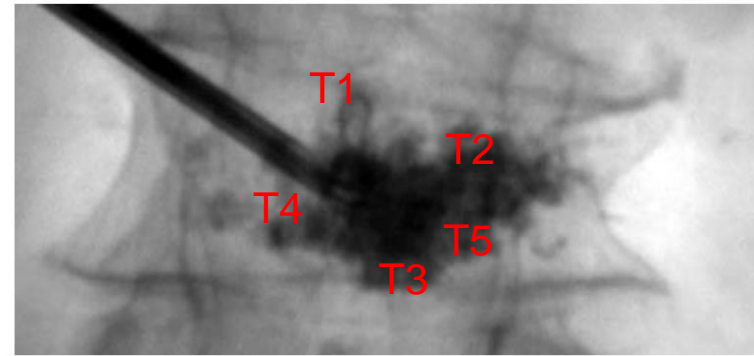
Vivo

- In vitro: T3 thermocouple embedded in cement

- In vivo: Thermocouples T2 and T5 embedded in cement while T1, T3, T4 at bone-cement interface

Experiment Results → In Vitro

Bone Cement/Thermocouple	Peak Temperature			Temperature over 50° C		
	T1	T2	T3	T1	T2	T3
Orthocomp	40.1±0.8°C	51.2±6.2°C	45.2±4.9°C	-	1.3±1.4 min	0.2±0.6 min
Simplex P	38.5±1.4°C	61.8±12.7°C	50.3±9.8°C	-	3.6±2.1 min	1.2±1.6 min

➢ On average temperature histories for Simplex greater and longer in duration than Orthocomp

➢ At T1, no substantial difference in peak temperatures between two cements

➢ At T2 and T3 the peak temperature was greater and longer for temperature above 50°C with Simplex cement than Orthocomp

➢ Overall temperatures liberated at thermocouples T2 and T3 might be significantly high and long in duration, potential of causing thermal necrosis of bone tissue

Experiment Results → In Vivo

Bone Cement Group	Thermocouple T2		
	Group A mean peak temperature $>60°C$	Group B $50°C <$ mean peak temperature $< 60°C$	Group C mean peak temper $<50°C$
Peak temperature	$86.7\pm10.7°C$	$60.5\pm3.7°C$	$44.8\pm2.6°C$
Temperature over 50°C	Average of all : 2 min 25s$\pm$1 min 17s Longer in Osteopal-V :5 min 7s$\pm$28s		42s$\pm$1 min 33s Osteofirm

➢ Peak temperature for vertebrae injected with Group A were significantly higher than those injected with Group B and C.

➢ In Group C temperatures did not reach 50°C and the average dwell time was less than 1 min

➢ Using Group C cements can significantly reduce or eliminate the possibility of thermal necrosis.

Assessment

Pros

➢ Well written workflow describing the experiment

➢ Providing an informative insight to temperature measurement of bone cement polymerization

➢ Vitro: Simulating physiologic conditions by placing VB in a saline bath at body temperature

➢ Vivo: Premier in vivo temperature measurement

➢ Vivo: Utilizing RFA needle with five thermocouples

Cons

➢ In vitro measurements may not be completely accurate since 10cc cement is not injected at the same time

➢ Vitro: Experiment setup is not clearly depicted

➢ Vivo: Temperature were not matched by histologic findings

➢ Vivo: It would be beneficial to include more details of the patients who underwent PV

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Significance and Key Results

❏ Thermal Finite Element Simulation study to evaluate temperature distribution

✓ Major complications of cementation:
    Thermal necrosis due to high heat generation during polymerization
    Chemical necrosis due to unreacted monomer release

✓ Finite element (FE) modeling scheme for distribution of temperature and monomer leftover after cementation

✓ Temperatures in the cement embedded trabeculae regions were much higher than those in the bone-marrow region adjacent to the bone-cement interface

✓ Bone tissue with highest temperature also subjected to high leftover monomer concentration

Technical Approach

- Cube of bovine trabecular bone

- Cement mixed and placed directly on the bone surface within a rubber ring

- Micro CT scan of the specimen

- Sub-Volume: 1.75mm✕1.75mm✕5.95mm

- Identification of domains of marrow, cement and bone using two level threshold

- 3-D computer model of bovine cancellous bone created
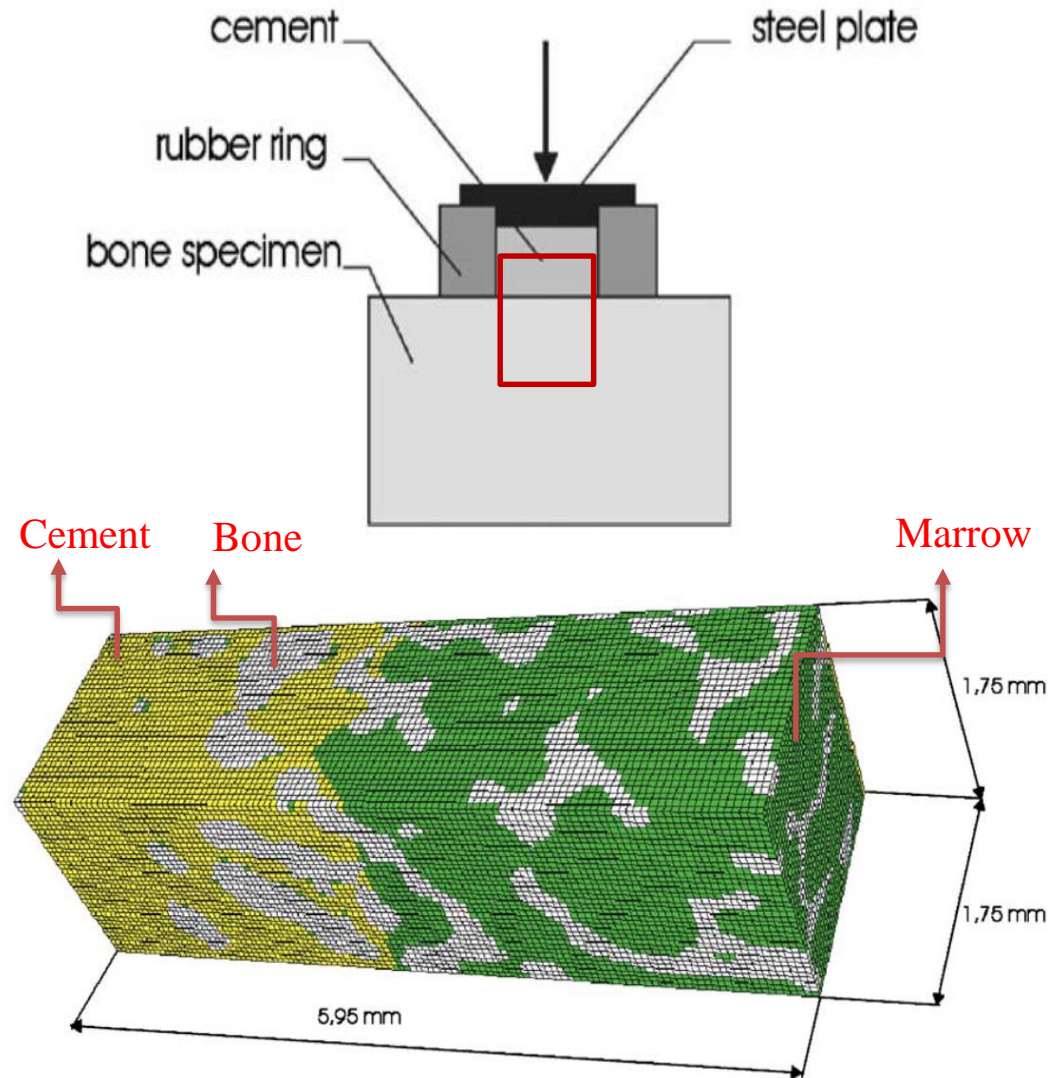
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Temperature field equations

$$\frac{\partial T(\mathbf{x}, t)}{\partial t} = a_i \nabla^2 T(\mathbf{x}, t) + q_v(\mathbf{x}, t) \quad \text{in } \Omega_i,$$

$$q_v(\mathbf{x}, t) = \eta(\mathbf{x}, t) \frac{Q}{\rho_1 c_1} \frac{\partial w(\mathbf{x}, t)}{\partial t}$$

$$\eta(\mathbf{x}) = \begin{cases} 1 & \text{if } \mathbf{x} \in \Omega_1, \\ 0 & \text{otherwise.} \end{cases}$$

Kinetic equation for the polymerization fraction w

$$\frac{\partial w(\mathbf{x}, t)}{\partial t} = a \exp\left(-\frac{E_a}{RT(\mathbf{x}, t)}\right) P(T(\mathbf{x}, t), w(\mathbf{x}, t)),$$

$$P(T, w) = \begin{cases} \frac{\alpha}{w^*(T)} w^{1-1/\alpha} (w^*(T) - w)^{1+1/\alpha} & \text{if } w < w^*(T), \\ 0 & \text{if } w \geq w^*(T). \end{cases}$$

$$w^* = \begin{cases} \frac{T}{T_g} & \text{if } T \leq T_g, \\ 1 & \text{if } T > T_g, \end{cases} \quad T_g = 378 \text{ K}$$

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Initial Condition

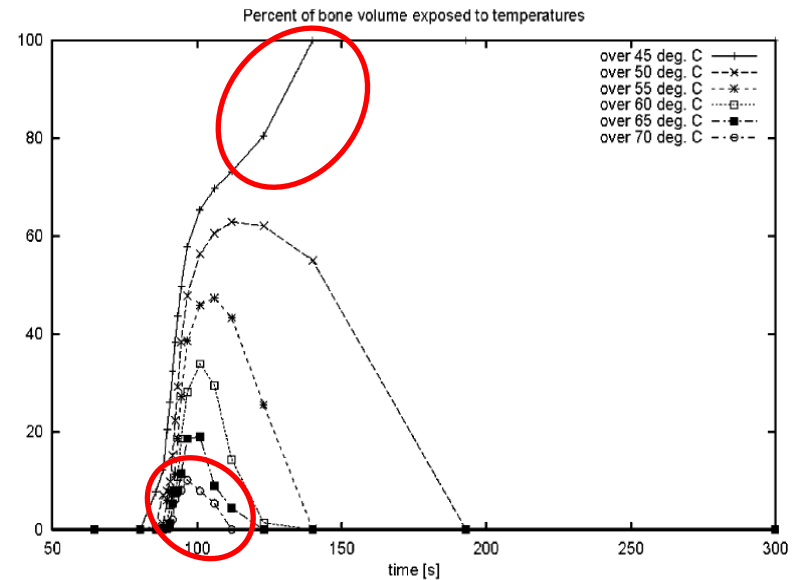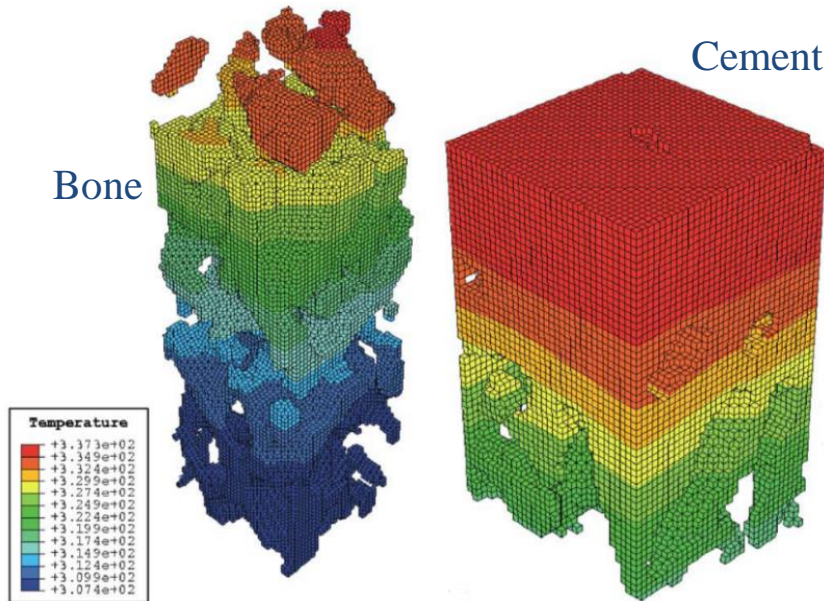$$T|_{t=0}(\mathbf{x}) = 300 \text{ K}, \quad w|_{t=0}(\mathbf{x}) = 0.01.$$

Boundary Condition

- Adiabatic Condition on all walls perpendicular to interface and leftmost wall
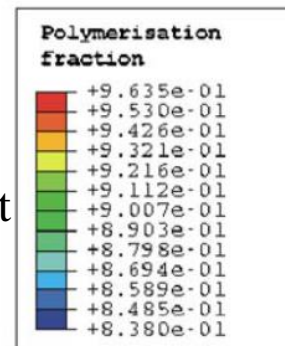- Free convection on the rightmost wall

Cement   Bone   Marrow

1,75 mm

1,75 mm

5,95 mm
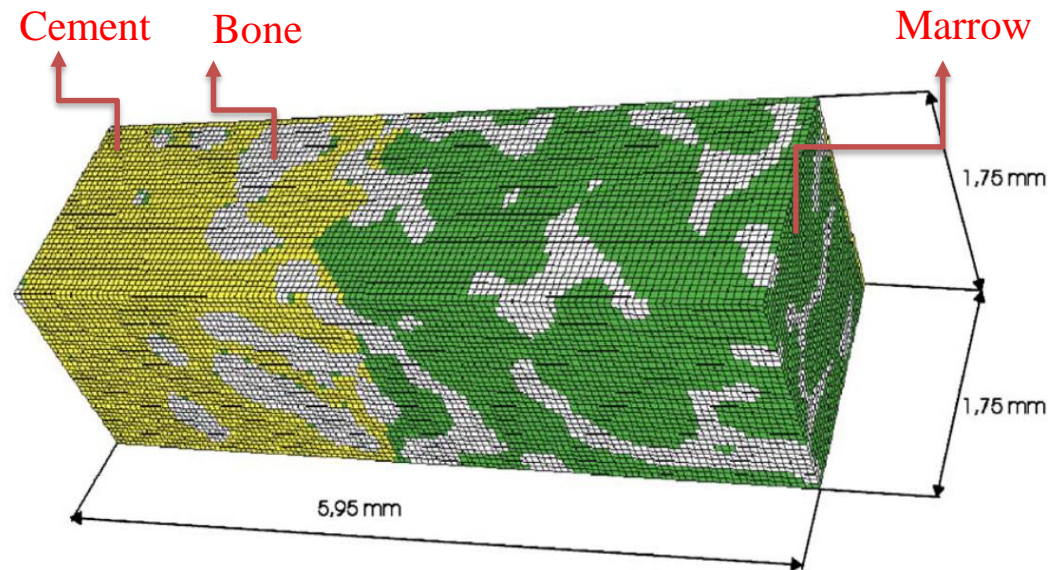
Simulation Results

➢ Distribution of temperature for possibility of thermal necrosis during polymerization

Cement

Bone

- Maximum temperature in the bone or cement (337 K) is much higher than temperature in the bone/marrow region (307 K)
- All the bone is exposed to a temperature higher than 45°C from t=140 s until the end of analysis
- Only 10% of the bone were subjected to temperatures higher than 70° C with dwell time of 50s

Simulation Results

➢ Distribution of monomer leftover for possibility of chemical necrosis during polymerization

- Cement polymerization fraction at the Centre is higher than in the region near the bone

- Polymerization at the Centre of the cement is more complete than that near the bone interface.

- Polymerization at the Centre of the cement occurs earlier

Polymerisation fraction
- +9.635e-01
- +9.530e-01
- +9.426e-01
- +9.321e-01
- +9.216e-01
- +9.112e-01
- +9.007e-01
- +8.903e-01
- +8.798e-01
- +8.694e-01
- +8.589e-01
- +8.485e-01
- +8.380e-01

Cement

Assessment

Pros

➢ Well written workflow describing the development of simulation

➢ Providing a good insight to thermal finite element modeling of cement polymerization

➢ Developing a realistic microstructure bone-cement architecture and realistic temperature-dependent polymerization FE model

➢ Using more accurate material properties by separating bone and marrow

Cons

➢ Homogenous material instead of inhomogeneous

➢ Thermal conditions were not described and depicted clearly

➢ It is not clear that the bone-cement interface model can be relied for cemented implant or after vertebroplasty

➢ Cement penetration found is expected to be higher than that in clinical practice

Relevance and Takeaways

➢ Recorded surface temperature of the bone using three k-type thermocouples placed at neck, trochanteric crest and intertrochanteric line for femur
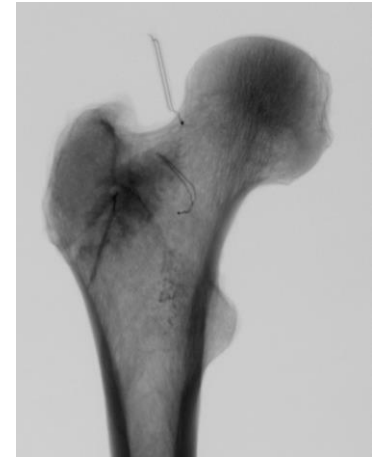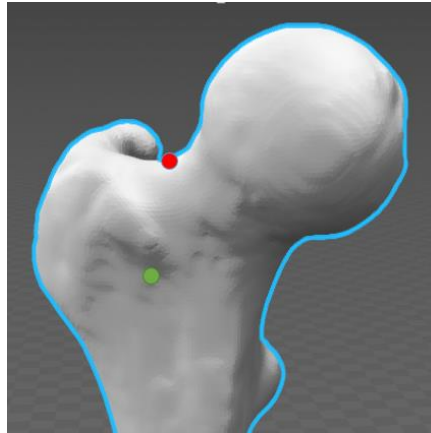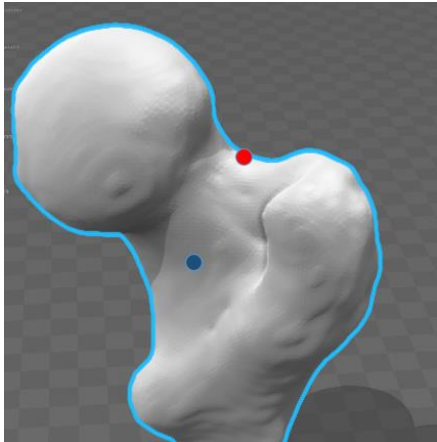
➢ Similar workflow to segment bone and cement as homogeneous continuum materials and simulate the heat transfer model using temperature field equations

➢ Femoroplasty, utilizes a larger volume of PMMA, the effects of bone cement injection causing risk of thermal necrosis must be taken into consideration

Questions?

Thank you