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FROM CT SCAN TO PLANTAR PRESSURE MAP DISTRIBUTION OF A 3D ANATOMIC HUMAN FOOT

Pasquale Franciosa **Salvatore Gerbino**

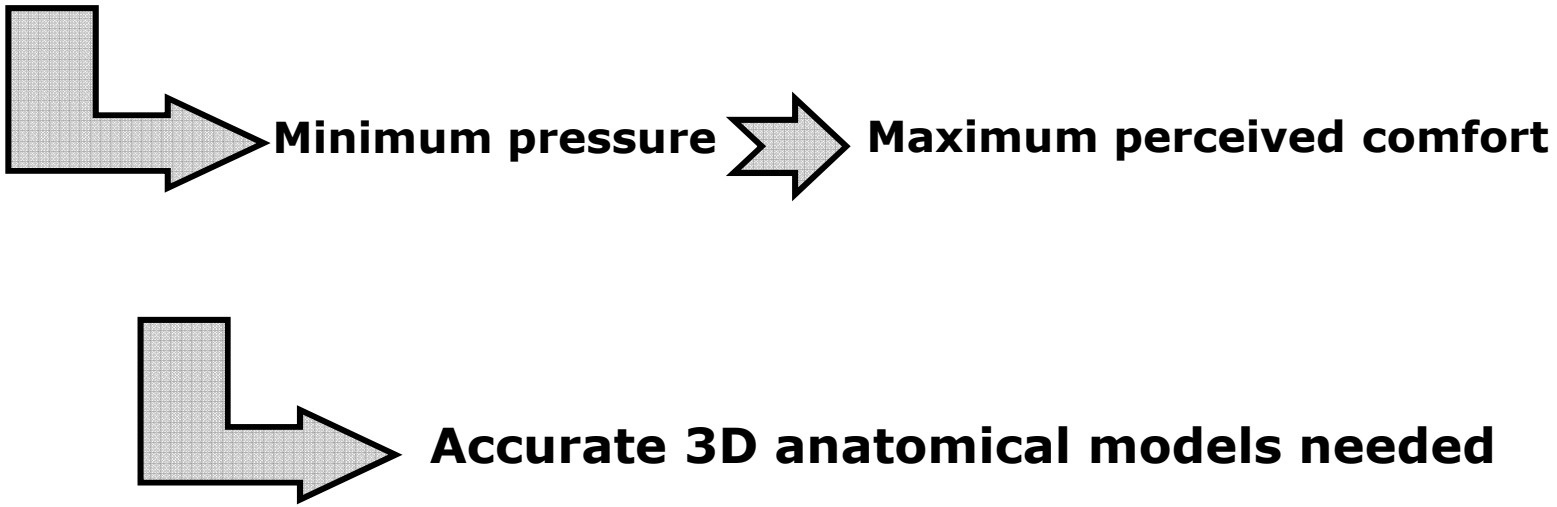
University of Molise
School of Engineering - Italy

Outline

- Introduction and Aims
- From CT images to numerical results
  - ✓ CAD modeling
  - ✓ FE modeling (non-linear material law, contact analysis)
- Numerical Issues
- Result Analysis
- Final Remarks

Introduction and Aims

- Stress-strain behavior of human foot tissues and pressure map distributions at the plantar interface are of interest
- Plantar pressure maps highly influence perceived **human comfort** at insole footwear interface.



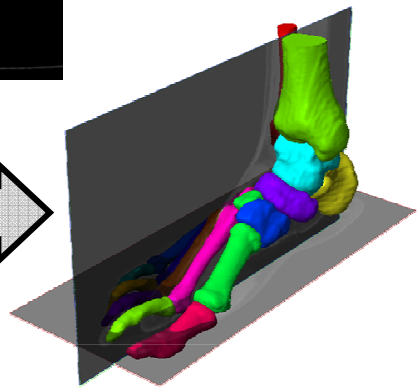
… in this work

- Building-up 3D human foot model into **Comsol Multiphysics® 3.5a**
- Facing out numerical issues:
  - ✓ *Non-linear materials*
  - ✓ *Contact analysis*
  - ✓ *Large deformation*

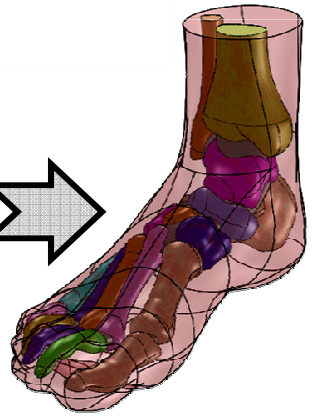
Methodology Overview

Foot CT scan images
.DICOM format
(Toshiba® Aquilion 4)

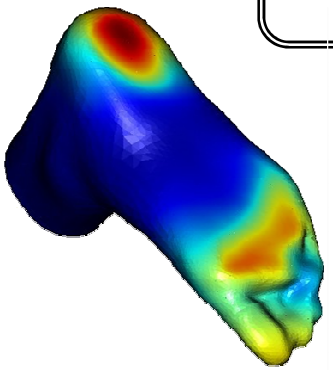
3D Image reconstruction
.STL format
(ScanIP® module 3.2)



CAD modeling
live-link
(SolidWorks® 2010)

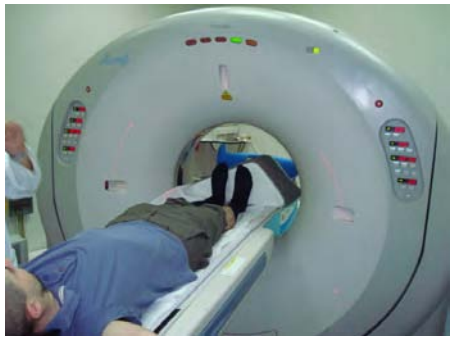


FE modeling
(Comsol Multiphysics® 3.5a)

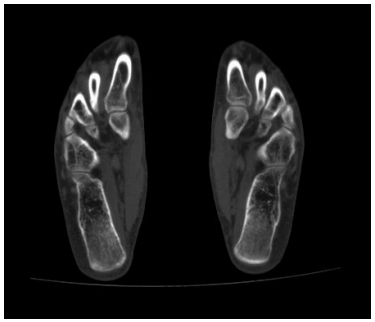


Methodology Overview

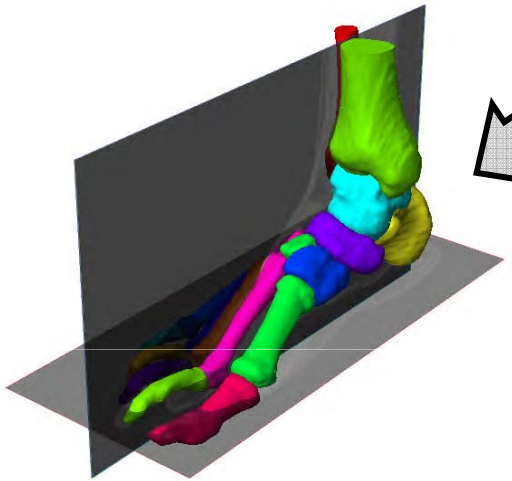
Image Processing



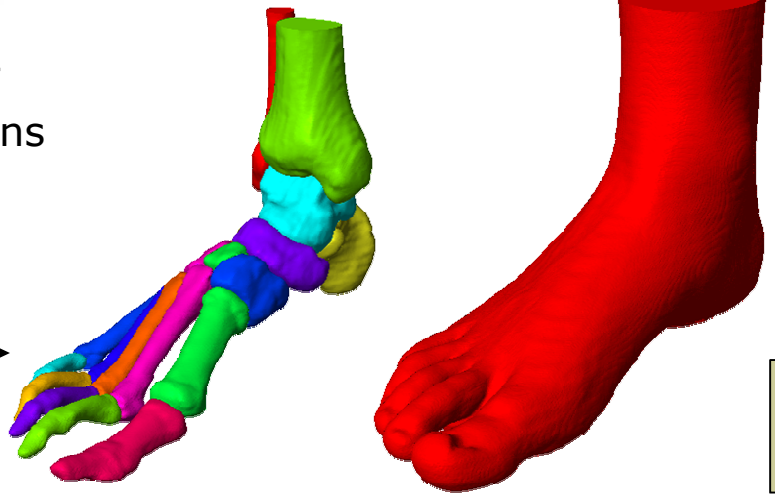
Toshiba® Aquilion 4
(29 years old male)



345 slices
1.00 mm slice distance
512x512 image resolution



.STL format of
segmented regions

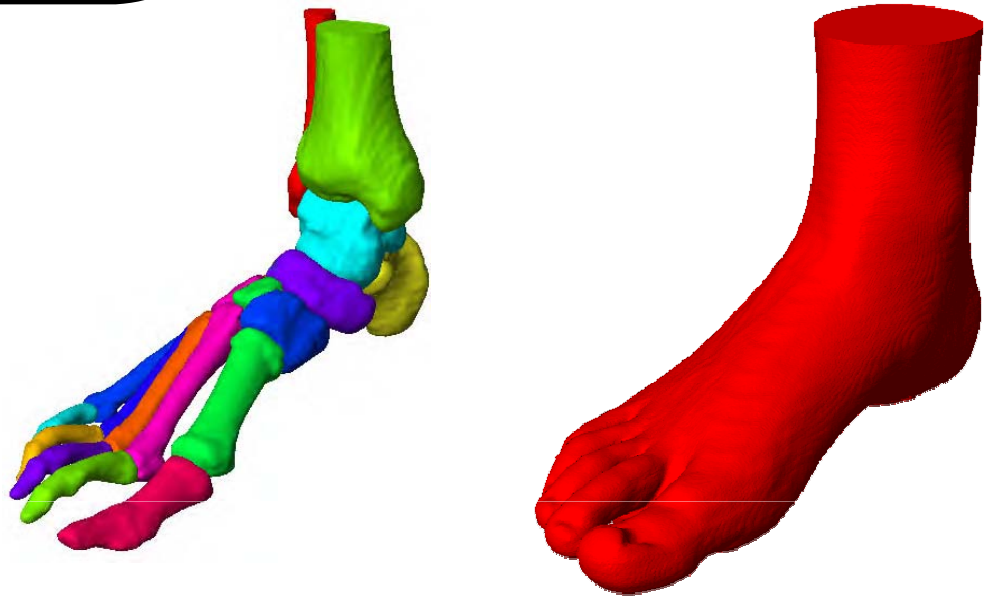


Bone structure and soft tissue

SCANIP® module, by
Simplewere®, adopted

Methodology Overview

Image Processing



- 19 bones segmented: tibia, fibula, talus, calcaneus, cuboid, navicular, 3 cuneiforms, 5 metatarsals bones,5 components of the phalanges
- Phalanges fused together since their relative motion do not affect plantar pressures
- Cartilages not extracted into the segmentation phase.

Methodology Overview

Image Processing | **CAD Modeling**

- When Comsol Multiphisycs® tries to directly import a tessellated model it generates some surface patches
- This procedure may generate some errors that user cannot directly control or fix
- Typically the geometry decomposition error is returned for imported multi-domain geometry

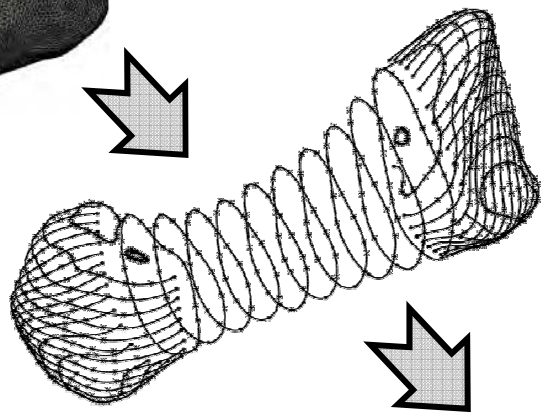
…

- … then, CAD model was created into CAD system and so it was imported into Comsol Multiphisycs®…

Methodology Overview

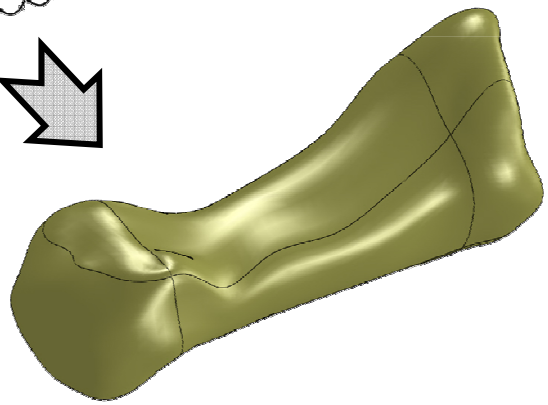
Image Processing | **CAD Modeling**

Tessellated model



Cross-section curves

3D CAD model

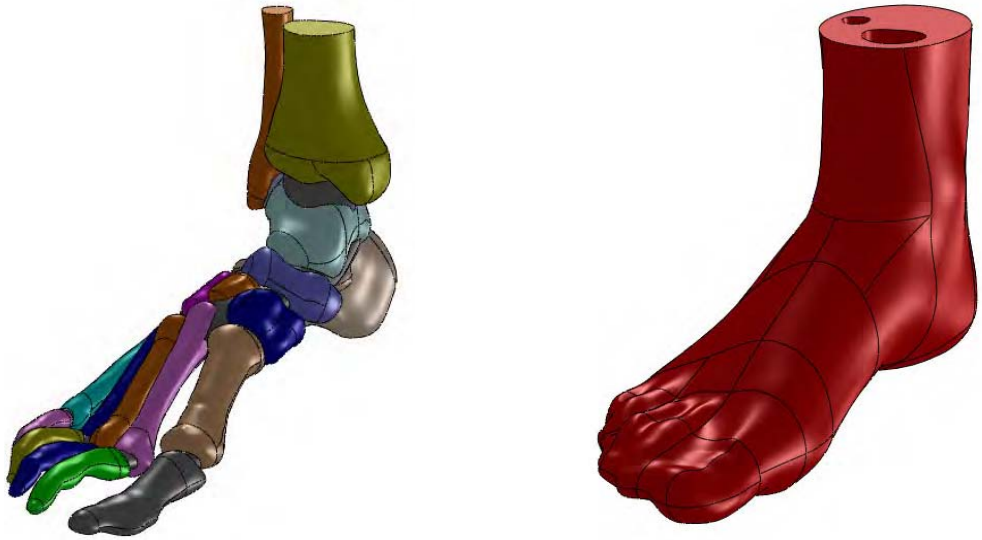


… starting from cross-sections lofting/sweeping/filling surfaces were generated…

SolidWorks® CAD system used with **SCANto3D®** add-in module

Methodology Overview

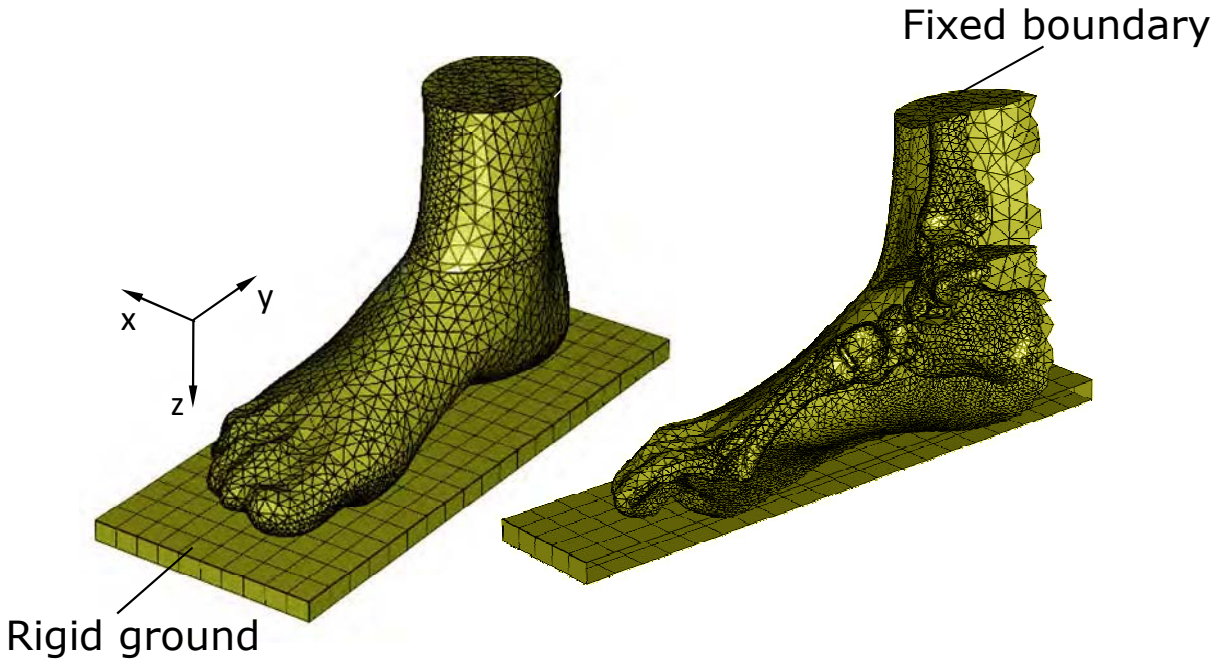
Image Processing | **CAD Modeling**



- Cartilages modeled in order to joint bones and fill the cartilaginous space
- Boolean operations used to ensure congruence among the related interfacial surfaces
- Toes at soft tissue level merged together.

Methodology Overview

Image Processing | CAD Modeling | **FE Modeling**



- Domain equations, boundary conditions and solver settings provided
- The foot supposed to touch an ideal-rigid flat ground.

Methodology Overview

Image Processing | CAD Modeling | **FE Modeling**

Domain Equations

- Soft tissue – **non-linear hyper-elastic behavior**

$$W(II_1, II_2, J) = C_{10}\cdot(II_1-3)+C_{01}\cdot(II_2-3)+C_{20}\cdot(II_1-3)^2+C_{11}\cdot(II_1-3)\cdot(II_2-3)+\ldots$$
$$+C_{02}\cdot(II_2-3)^2+\frac{1}{D_1}\cdot(J-1)^2+\frac{1}{D_2}\cdot(J-1)^4$$

Constant	Value
C_{10} (N/m^2)	85550.0
C_{01} (N/m^2)	-58400.0
C_{20} (N/m^2)	38920.0
C_{11} (N/m^2)	-23100.0
C_{02} (N/m^2)	8484.0
D_1 (m^2/N)	0.4370e-5
D_2(m^2/N)	0.6811e-6

… data from literature

- Bones – linear and isotropic material

  E=7300 MPa, v=0.3

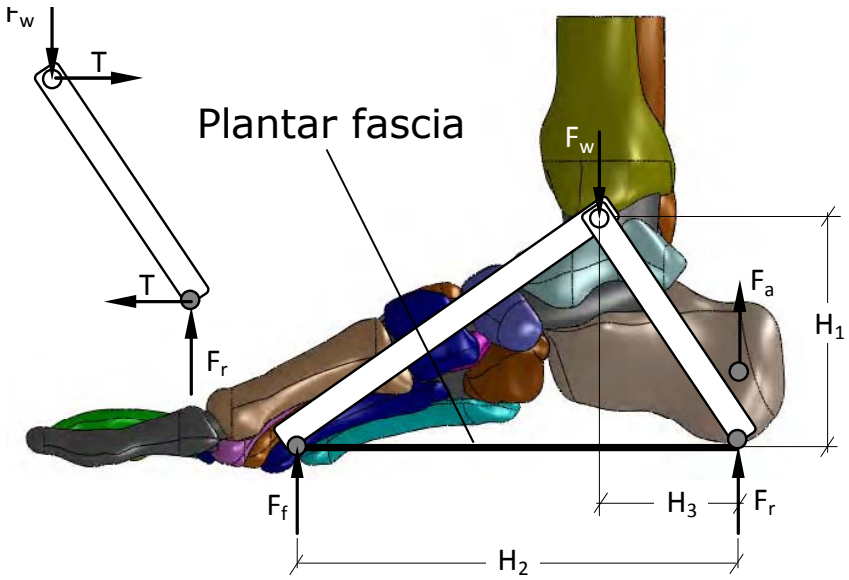
- Cartilages – linear and isotropic material

  E=10 MPa, v=0.4

Methodology Overview

Image Processing | CAD Modeling | **FE Modeling**

Domain Equations | **Boundary Conditions**



Equivalent Loads

$$\begin{cases} F_r = \dfrac{F_w \cdot (H_2 - H_3)}{H_2} \\ T \cdot H_1 = F_r \cdot H_3 \end{cases} \rightarrow T = \frac{F_w \cdot (H_2 - H_3)}{H_2} \cdot \frac{H_3}{H_1}$$

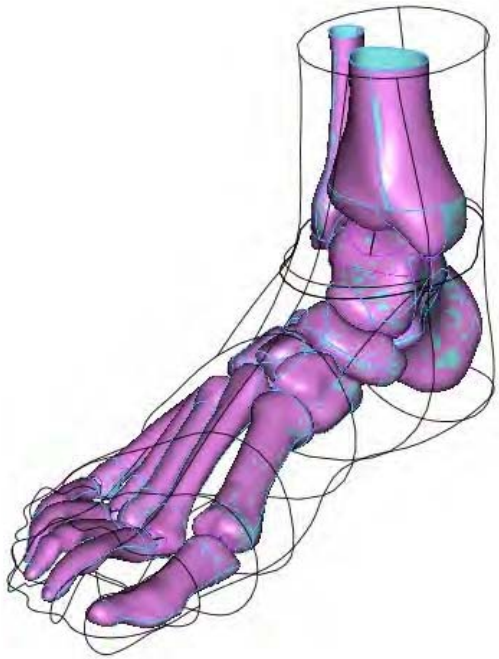
$$T = 0.4268 \cdot F_w$$

- A vertical force, corresponding to one half of the body weight (F_w=650/2 N), transferred from the body to the foot and then to the ground
- The plantar fascia stabilizes the longitudinal arch of the foot and supports the longitudinal forces during the weight application phase
- Plantar fascia simplified and modeled by defining equivalent longitudinal forces (**$T \approx 0.5 \cdot F_w$**)

Methodology Overview

Image Processing | CAD Modeling | **FE Modeling**

Domain Equations | **Boundary Conditions**



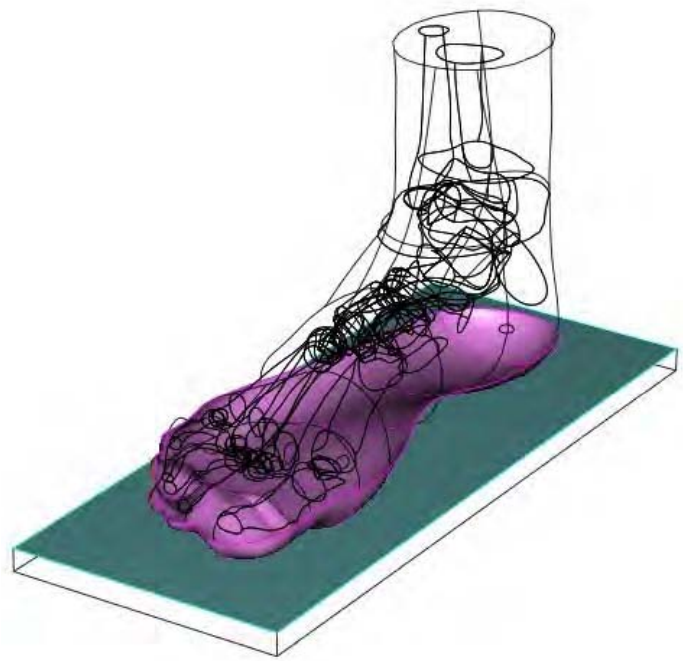
Identity Pairs

- Physical interaction among bones-soft tissue and bones-cartilages modeled by defining identity pairs among interfacial surfaces.
- Displacement fields at interfacial surfaces are identical each-other.

Methodology Overview

Image Processing | CAD Modeling | **FE Modeling**

Domain Equations | **Boundary Conditions**



Contact Pairs

- Plantar pressures are of interest
- Contact pairs among plantar surfaces and ground-surface defined
- No friction accounted into the analysis
- Foot and ground supposed to be not in contact initially.

Methodology Overview

Image Processing | CAD Modeling | FE Modeling | **Numerical Issues**

Contact Pairs

- Initial contact pressure:

$$P_n=0 \text{ (no contact initially)}$$

- Scaling factor (related to contact pressure variables):

$s_f=F_w/A_c$ (F_w: applied load. A_c: estimated final contact area)

- Penalty factor:

$p_n=s_c \cdot E_e/h_{mesh}$ (s_c: correction factor. Ee: equivalent elastic modulus. h_{mesh}: mean mesh size)

… **Fine tuning** all these parameters was not a trivial task.

✓ With a “trial and error” approach, several experiments were conducted to carry out the optimal set of parameters, allowing to reach a valid solution into a reasonable time.

Methodology Overview

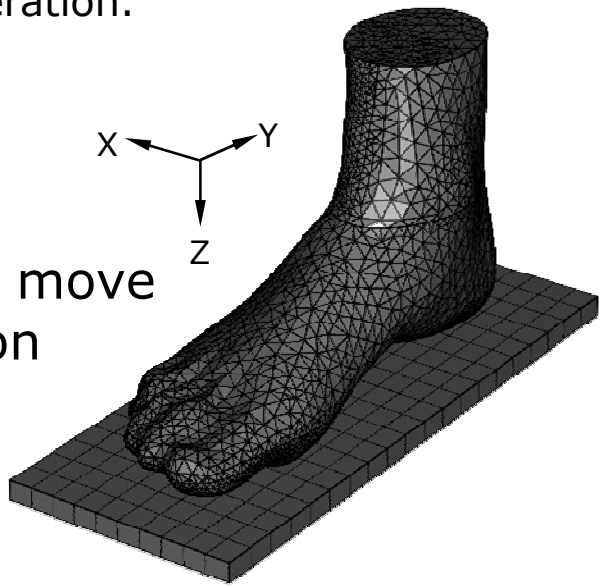
Image Processing | CAD Modeling | FE Modeling | **Numerical Issues**

Contact Pairs

… Another feature to be considered, when managing and solving contact problems, is the **constraint status** of each domain

- ✓ "Lack of constraints" causes problems with the convergence process into Comsol Multiphysics®
- ✓ All domains should be constrained in all directions, so that there is only one possible solution for each convergence iteration.

Ground domain supposed to rigidly move only along the global Z direction



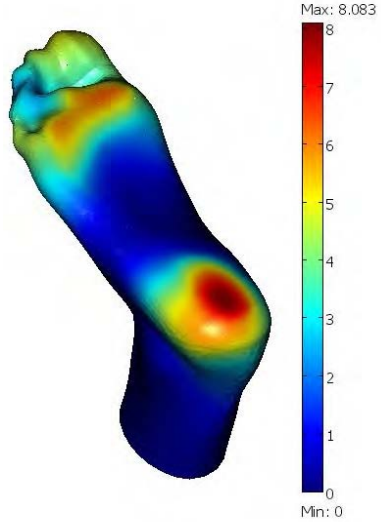
Methodology Overview

- Parametric solver adopted
- "PARDISO out of core" adopted as linear solver
- Final mesh made of 25812 nodes and 87149 elements
- Linear shape function used
- # of DoF solved for equal to 81428

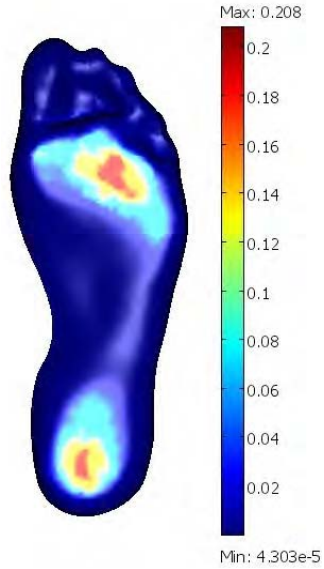
Numerical simulations were accomplished in about **100 min**

DELL Precision T7400 workstation
(WinXP 64bit, 16GB RAM, 2 Xeon E5420 quad-core processors)

Result Analysis

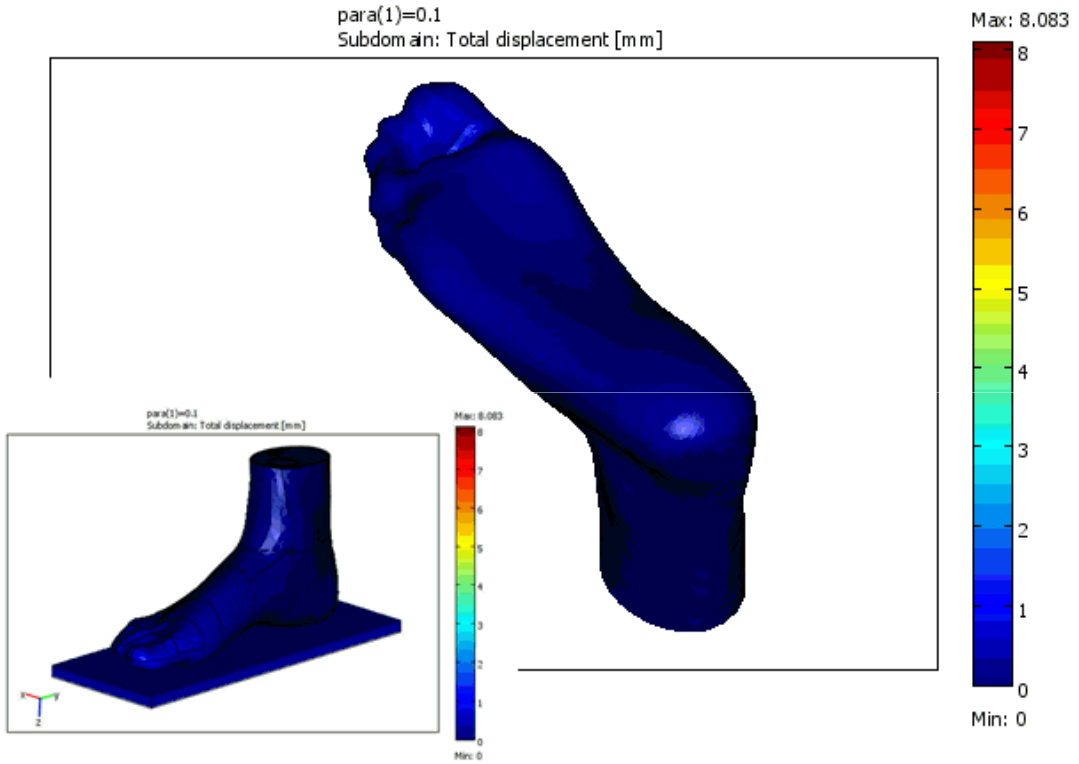


Total displacement [mm]



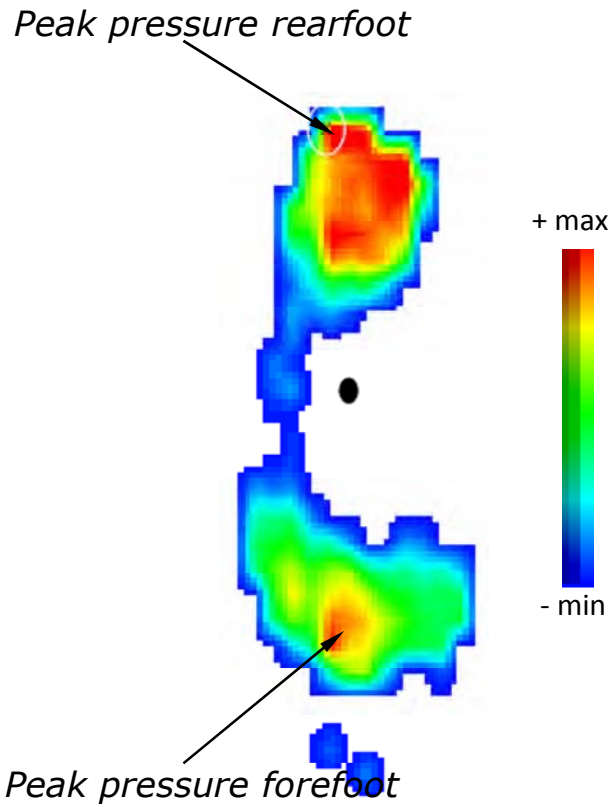
Plantar pressure map [MPa]

Movie-total displacement

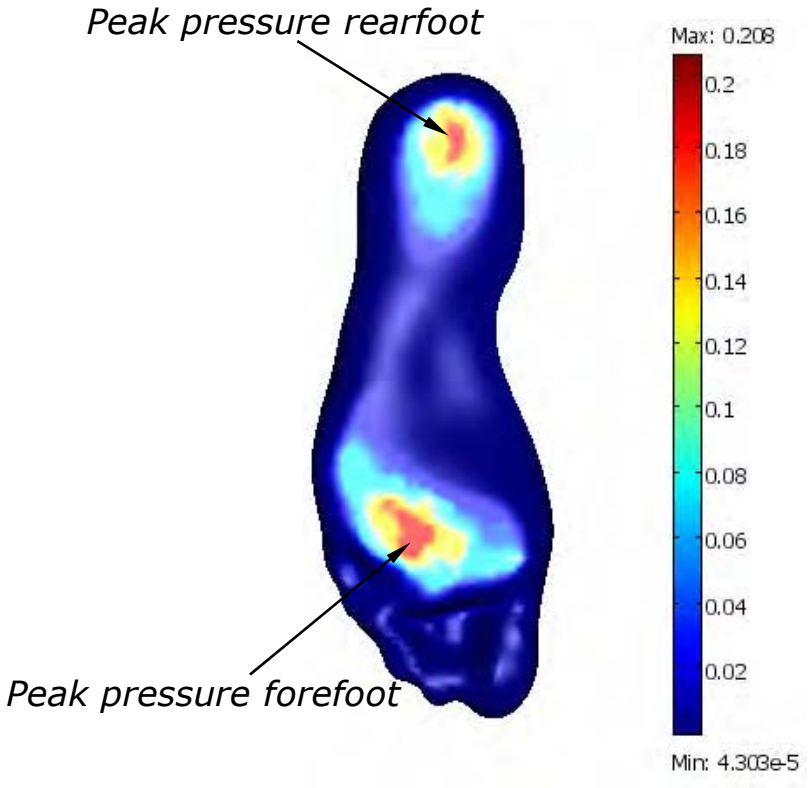


Experimental Validation

… high resolution insole sensors used to validate numerical results



Experimental results



Numerical results [MPa]

… regions with the peak pressure can be compared

Final Remarks

- Simulation of the balanced standing condition of a human foot model:
  - ✓ CAD model created from CT images
  - ✓ Hyper-elastic non-linear material law set
  - ✓ Contact pairs introduced to calculate plantar pressure maps
- Numerical issues pointed out:
  - ✓ Best choice of convergence parameters comes from some general rules along with a trial-and-error approach.
  - ✓ Manual fine-tuning numerical parameters is a very time consuming task.

… so, some improvements and suggested best practices to resolve model involving contact pairs are expected in the next future

Thanks for your attention!

Questions?

Pasquale Franciosa
pasquale.franciosa@unimol.it

Salvatore Gerbino
salvatore.gerbino@unimol.it