Using FEA to design 3D printed insoles for treating foot musculoskeletal disorders

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Context

Foot and ankle musculoskeletal disorders (MSDs) among workers:

→ (USA) 10 % of MSD work stoppage in 2015 [1]

→(FR) affects until 35% of workers in industry [2]

→ Prolonged standing position = important factor in the onset of MSDs among workers [3], [4]

→ Safety shoes aren't designed to protect against MSD in a work environment [5].

Context

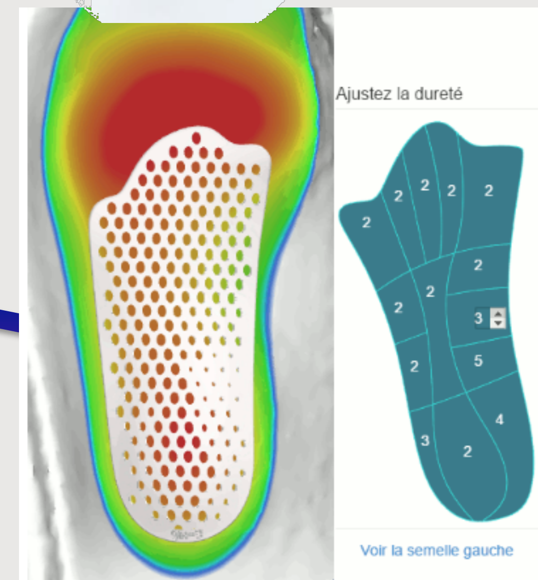
2

3D orthosis design

Proposed solution: A fully integrated process for podiatrists, in 4 steps

1

Clinical exam + Footscan



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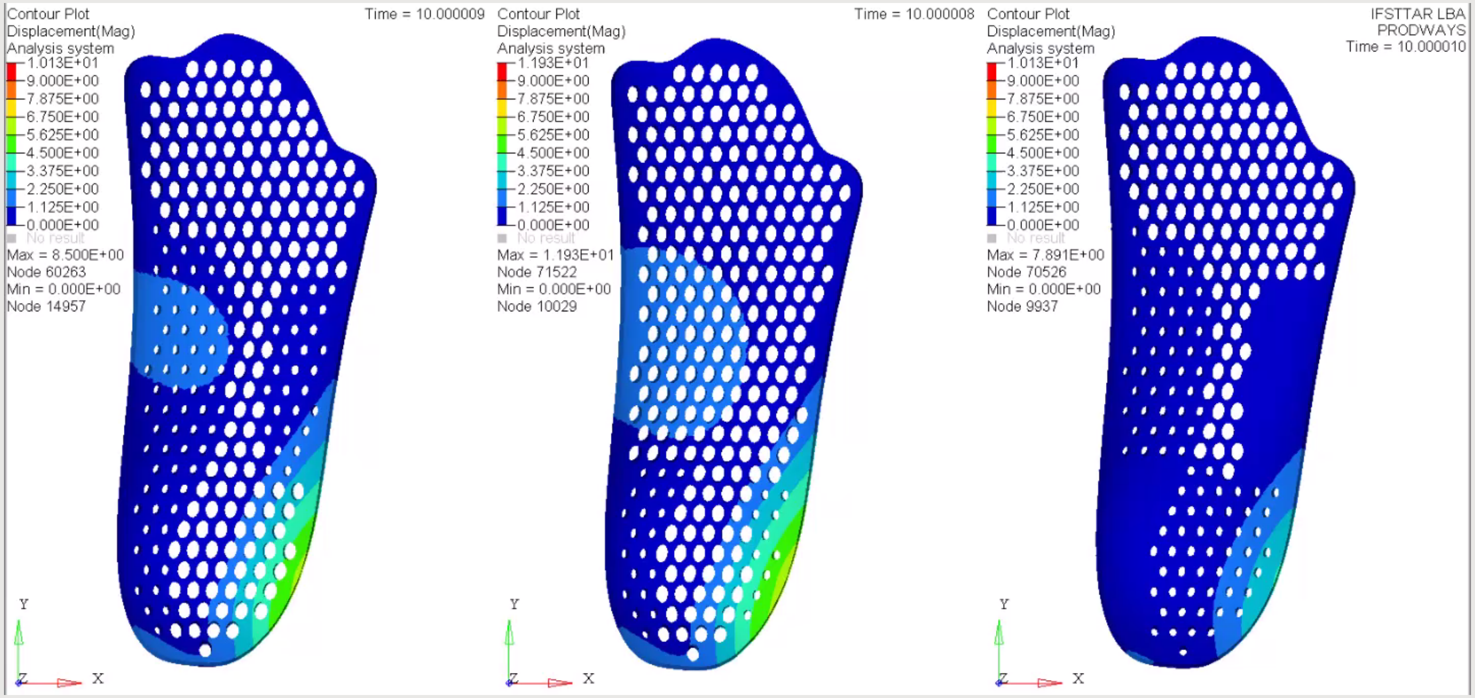
Distrubution

3

3D printing

Context

Any relation between design parameters and biomechanical function?



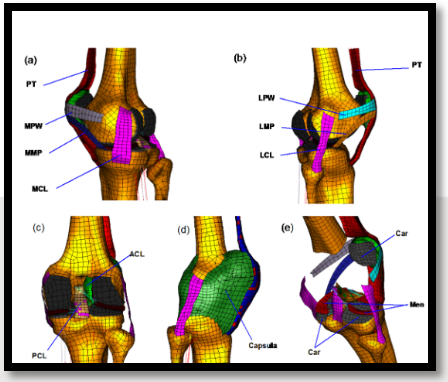
→ Significant Structural effects : predicting patient/ orthosis interaction is a complex problem

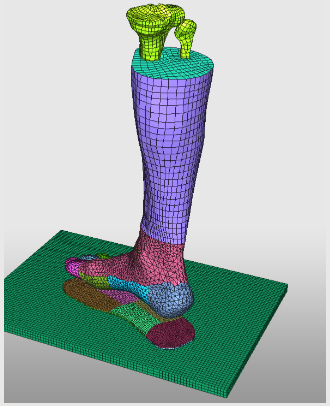
Simulations

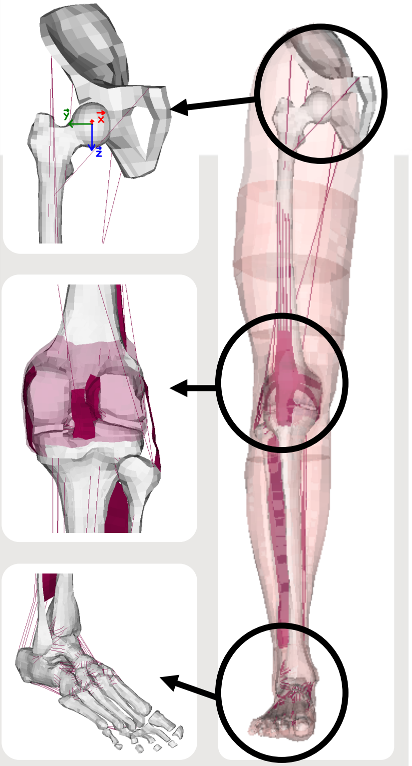
Step 1: the Foot-Leg FE model

Leg Model (LLMS) Validation

- Based on cadaver and volunteers tests
- Materials (ligaments, tendon, bones)
- Isolated segments(ankle, knee…)
- Foot-Leg complex (multi directional impacts)





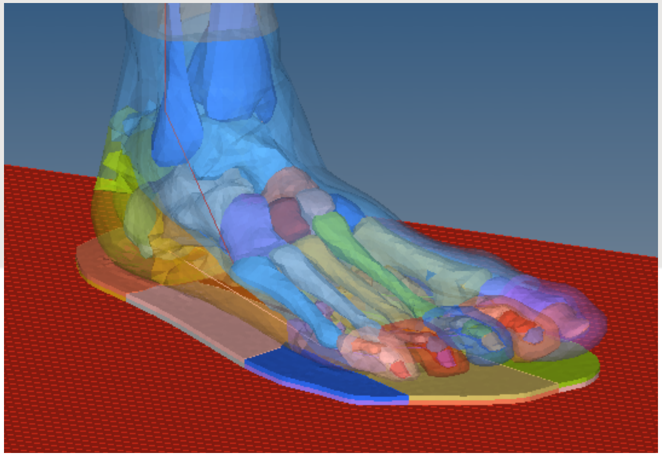


Varying Parameters

Joints : centers coordinates, reference systems

Joint Stiffness : General springs with varying Ts and Rs

Tibia orientation : Gait and Foot Arch height is affected by Tibia initial orientation



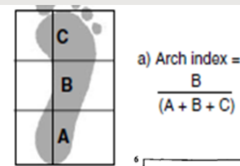
Simulations

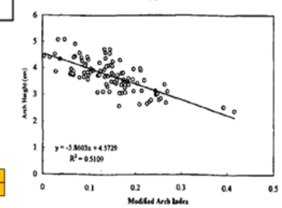
Step 2: scaling to the patient's characteristics

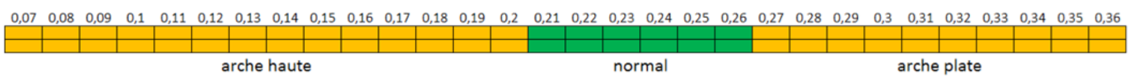
1. Anthropometry criteria (*PODOSCAN*)

2. Morphology criteria

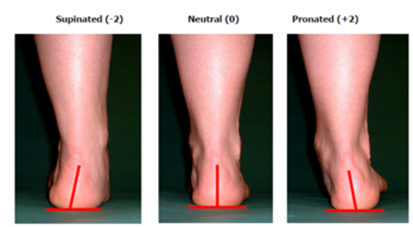
From the footprint: **Arch Index** (Cavanagh and Rodgers, 1987)
→ Considered as the most reliable (Murley et al, 2009)
→ static loading correlated with arch height –Chu et al, 1995, McCrory, 1997, Menz, 2005)
→ Easy to record



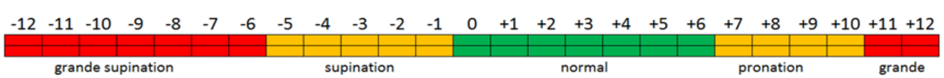




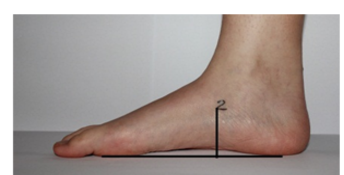
From visual analysis of patient: **Foot Posture Index**
→ Scaling the degree of pronation/supination
→ Total score from 6 variables (from -12 to +12)
→ Well correlated to arch height (Menz, 2005)
→ Mean value: +5



-2	-1	0	1	2
More than an estimated 5º inverted (varus)	Between vertical and an estimated 5º inverted (varus)	Vertical	Between vertical and an estimated 5º everted (valgus)	More than an estimated 5º everted (valgus)

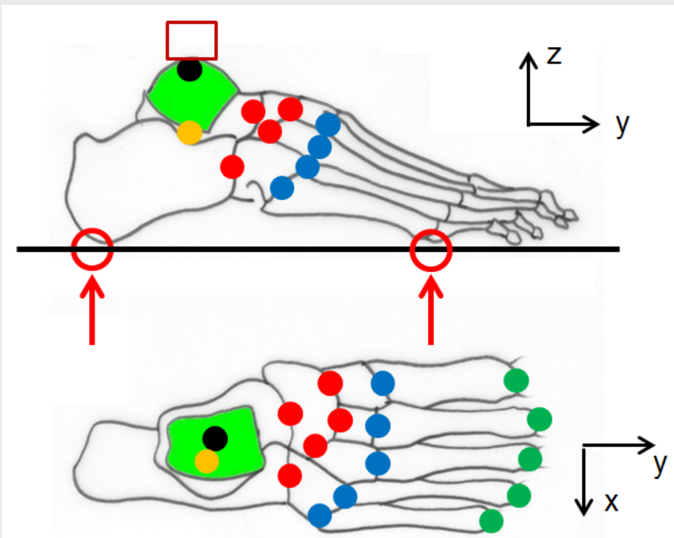


Navicular height: normalised Nav. Height Truncated (NNHt)
ICCs=0.67
Reliable and well correlated (Menz, 2005, Cowan, 1993)



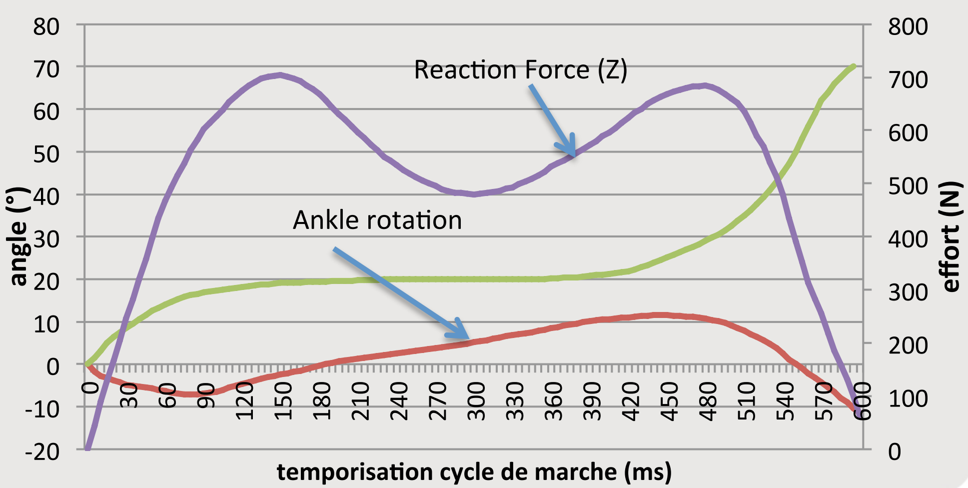
Simulations

Step 3: Gait boundary conditions



- Tarsal joints
- Metatarsal joints
- Phalanx joints
- Talo crural joint
- Sub talar joint
- BCs RB_tibia : constraint TZ
- Ground rotation center
- Load applied on ground

Joint= Spring SPR_8_GEN : TXYZ : RXYZ



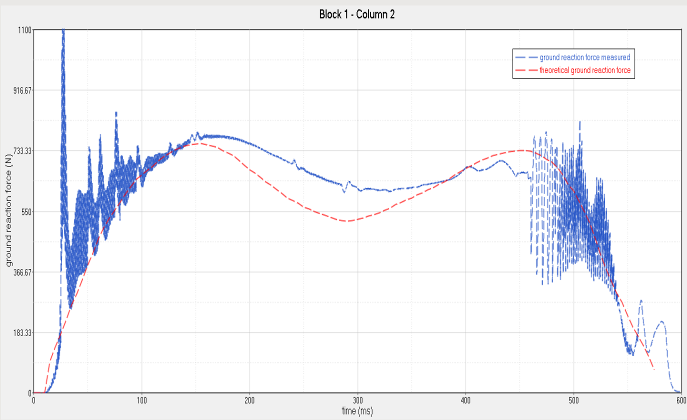
→displacements imposed from the « ground»

→free kinematics of the foot/ankle

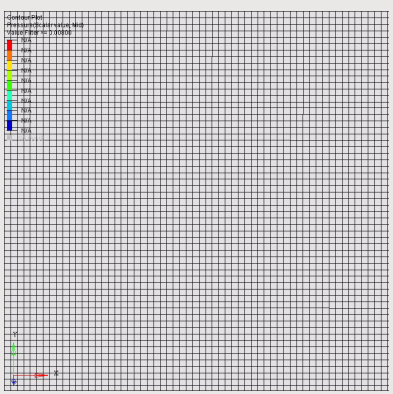
Simulations

Step 3: Gait boundary conditions

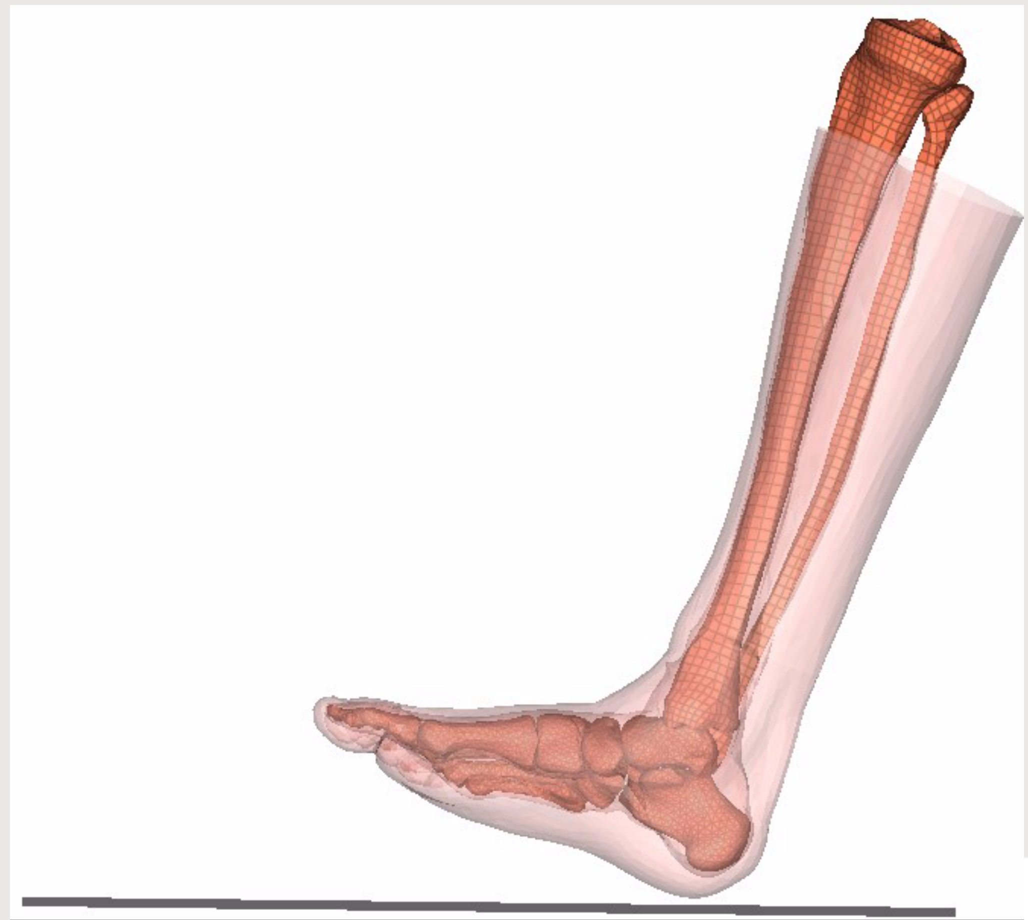
Normal gait - results



Ground reaction force



Plantar pressure distribution

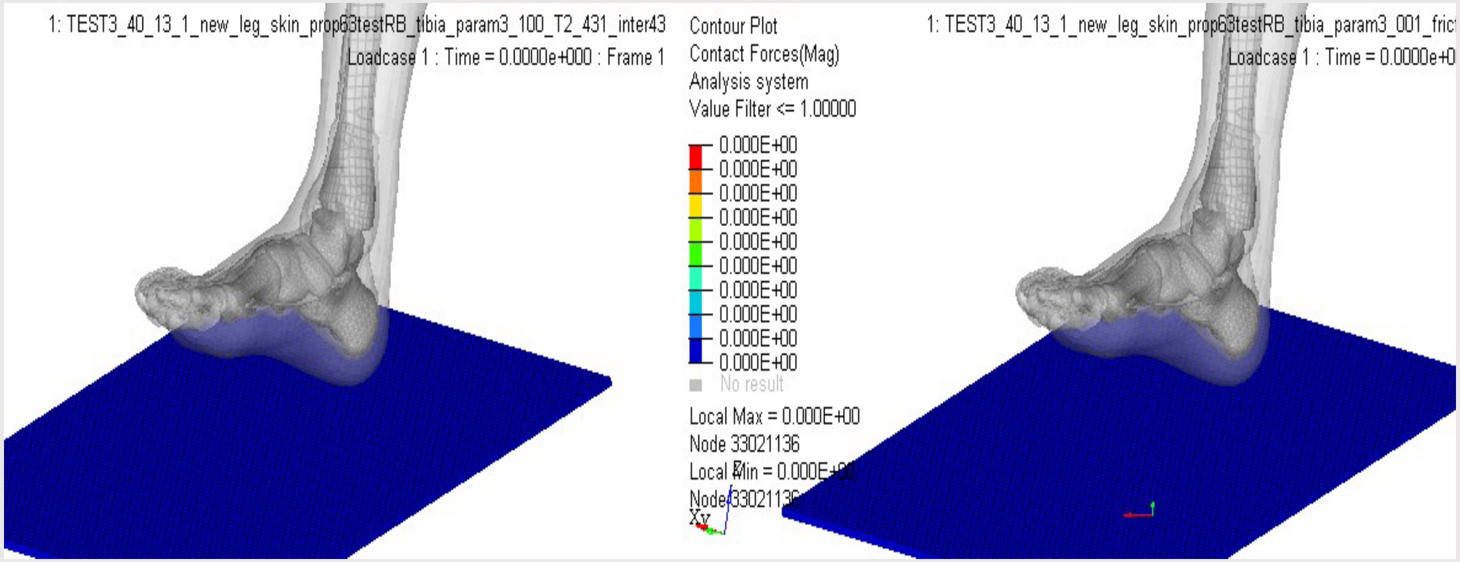


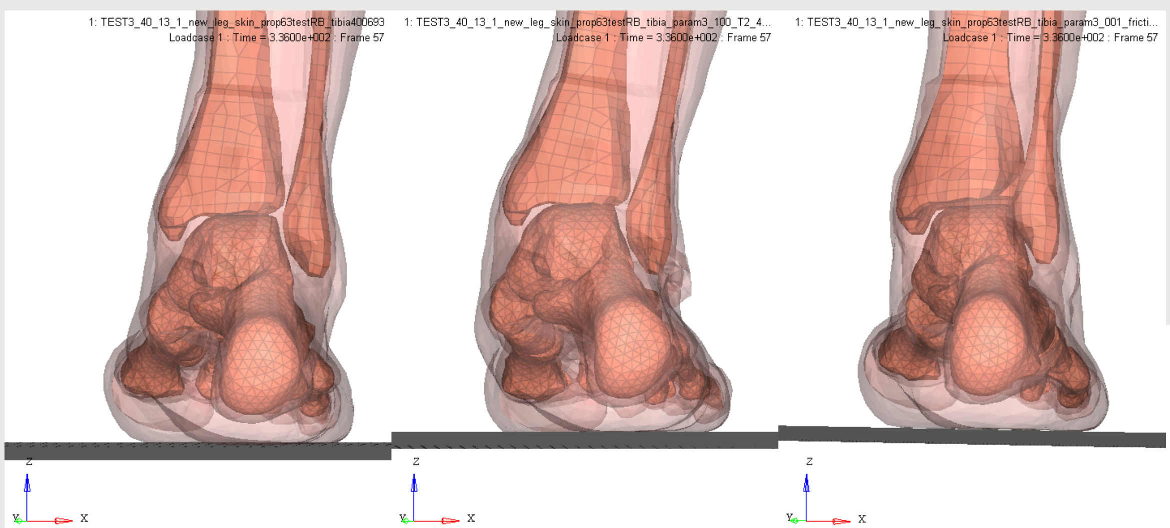
General kinematics

Simulations

Step 4: Varying walking gait characteristics

The sub-talar joint mobility is modified to simulate pronation/ supination in gait :

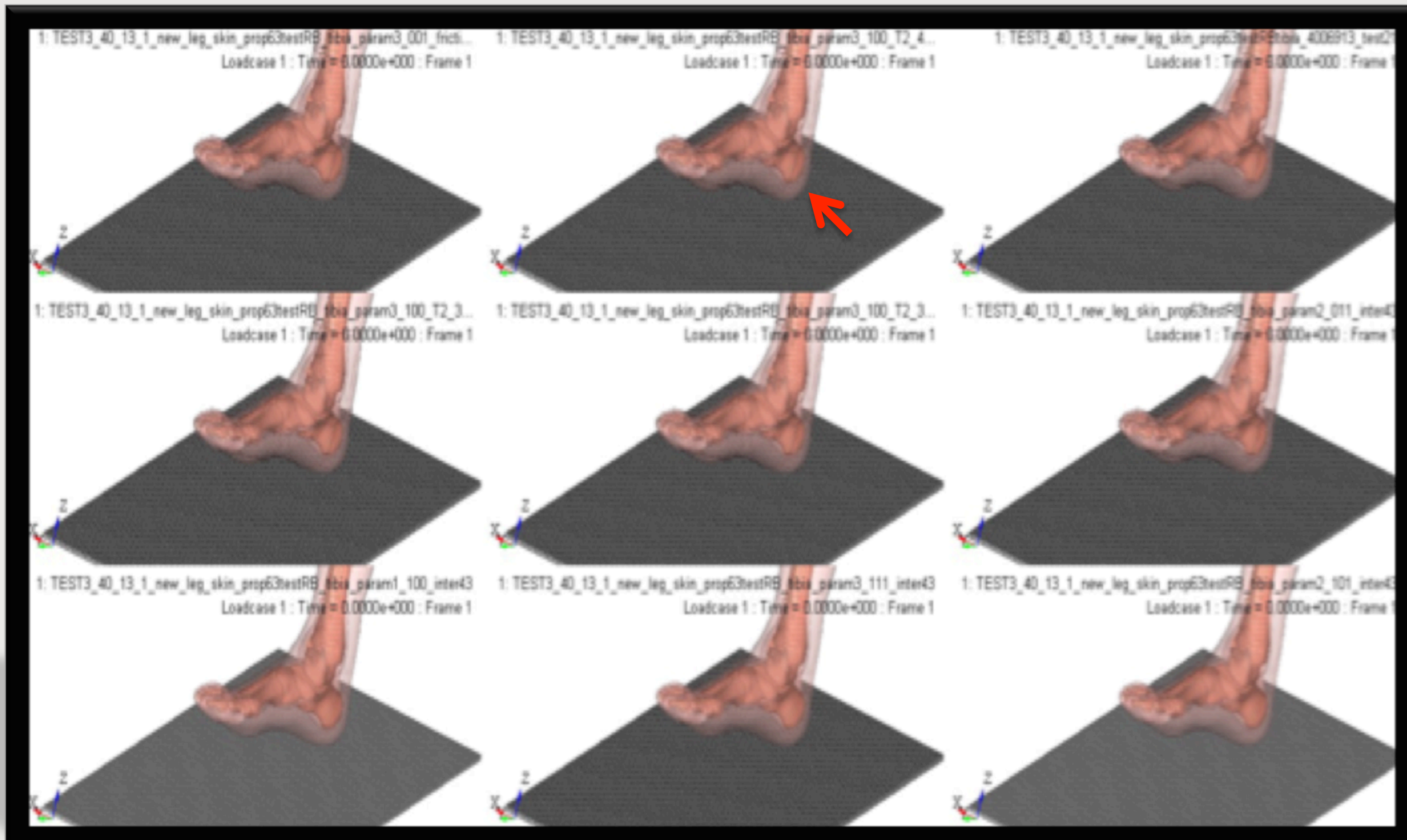




Simulations

Step 4: Varying patient's gait characteristics

Best matching case selection:



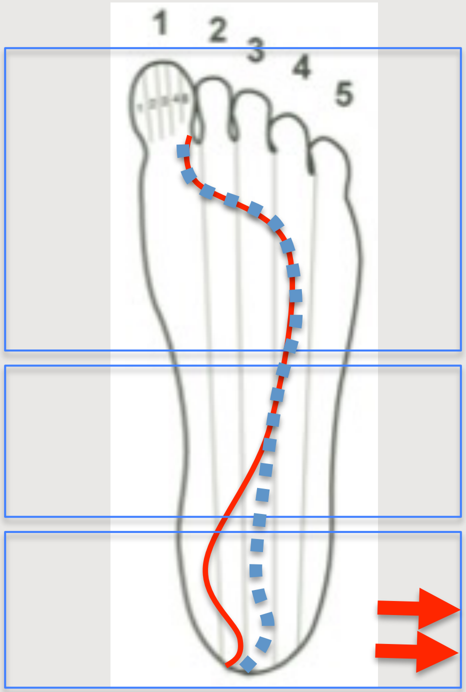
Simulations

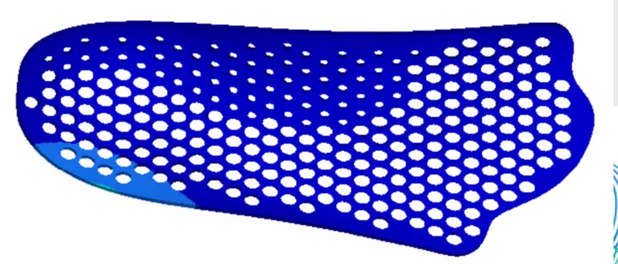
Step 5: Orthosis design

Efficiency criteria : the COP trajectory

Expert mode : the podiastrist defines the orthosis structure (and possibly, is given feedback)

Guided mode: the podiatrist defines the function expected on the COP trajectory, and a specific design is proposed
DOE Exploration :
    Thickness (1.5→2.5mm)
    holes sizes (4 different sizes)





Experimental Evaluation

34 standing workers suffering foot pain

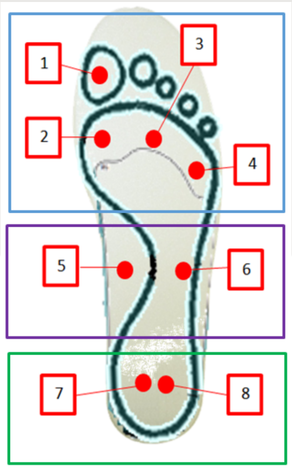
custom-made foot orthoses made by a trained podiatrist for all volunteers

Measurements at Day 1 and Day 21 (3 weeks of daily wearing)

- **Eyes closed**
- **60 seconds**
- **Force plate (Kistler) and Pressure sensors (anatoscope)**
- **2mn walk test**

Effect assesment

1. Static balance : Criteria based on COP displacement
2. Plantar pressures
3. Questionnaire (sclaes for conmfort, pain)



Experimental evaluation

- Significant improvement of balance in the medial-lateral and antero-posterior direction.

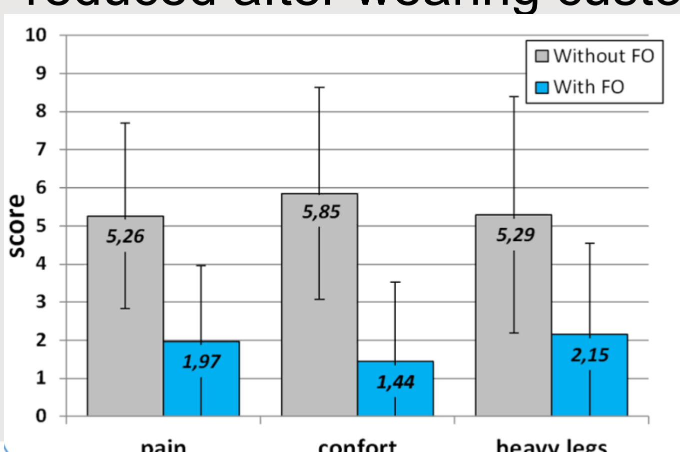
  Amplitude of anteroposterior displacement (mm): -23,7% Amplitude of medial-lateral displacement (mm): -34,0%

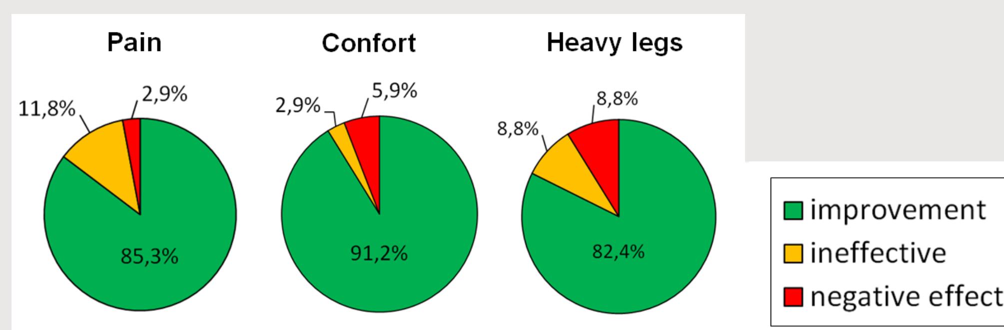
- Significant decrease in mean peak pressure in the rearfoot and in the whole foot areas ($p<0.05$).

- Significant increase in mean peak pressure in the midfoot area ($p<0.05$).

  Mean anteroposterior velocity (mm/s): -10,7% Mean medial-lateral velocity (mm/s): -23,5%

- Feelings of pain, discomfort and heavy legs were found to be significantly reduced after wearing custom-made orthoses ($p<0.05$).





Conclusions

- Encouraging results in podiatric therapy plannification,
- Objective Validation still requested in (double) blinded analysis
- Two next challenges:
  Real time design / level of decision making
- 3D scanners is a great opportunity for patient specific models