UNIVERSITÀ DEGLI STUDI FIRENZE
DIEF DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

ADDITIVE 4 BIOMEDICAL

October 17th–18th, 2022

OPTIMIZATION AND MATERIAL CHARACTERIZATION OF A 3D PRINTED COMPOSITE PROSTHETIC FOOT

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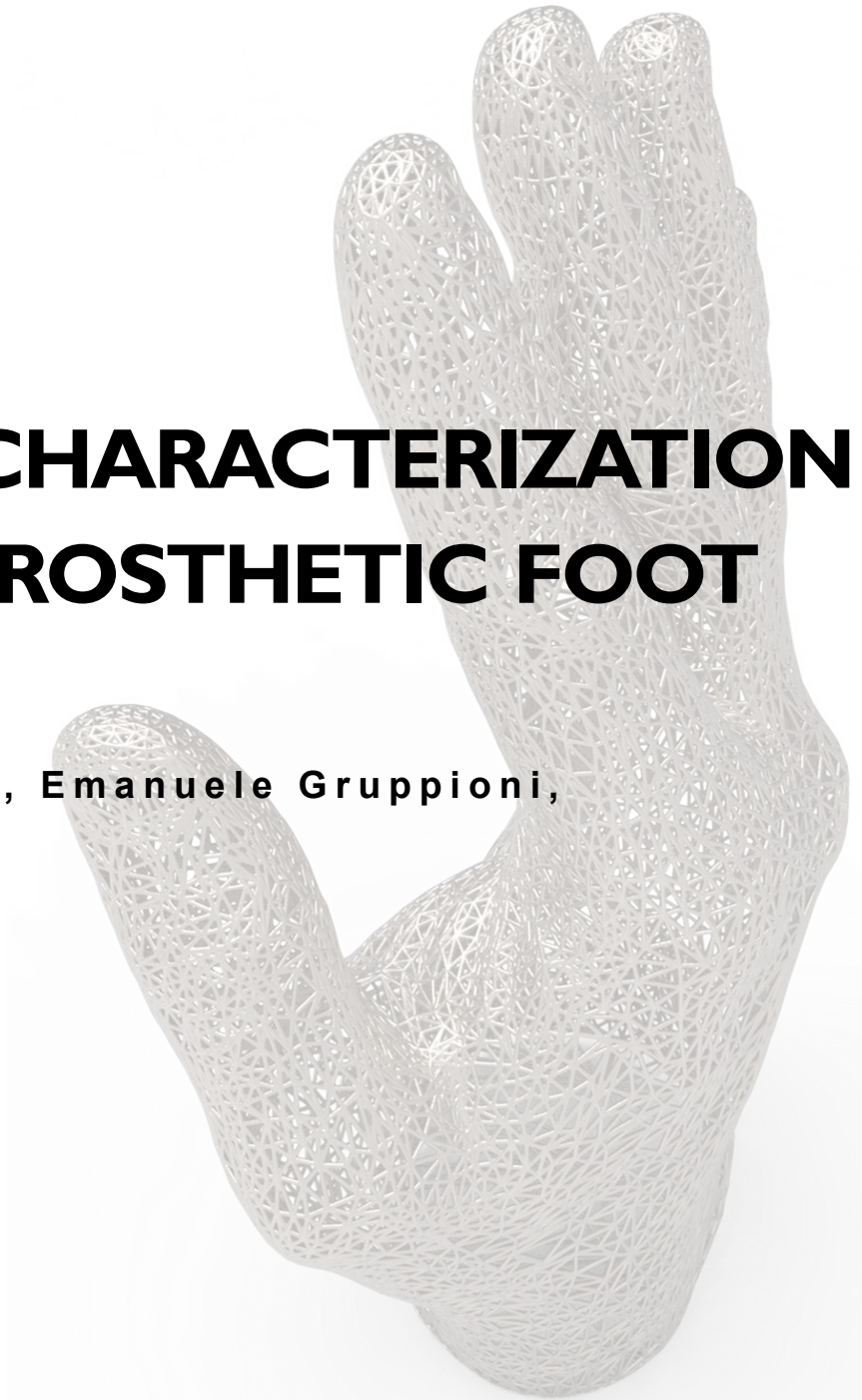
Luca M. Martulli, Andrea Sorrentino, Marino Lavorgna, Emanuele Gruppioni, Andrea Bernasconi

Plesso Didattico Morgagni, Viale Morgagni, 44-48, 50134 Firenze



SC.09/A3 CoCo AM Additive Manufacturing
ASSOCIAZIONE NAZIONALE DISEGNO E METODI
COMET
aias

MOTIVATIONS

Benchmark: Laminated composite foot prosthesis

- \+ Lightweight
- \+ Excellent mechanical properties
- − Expensive
- − Low customization

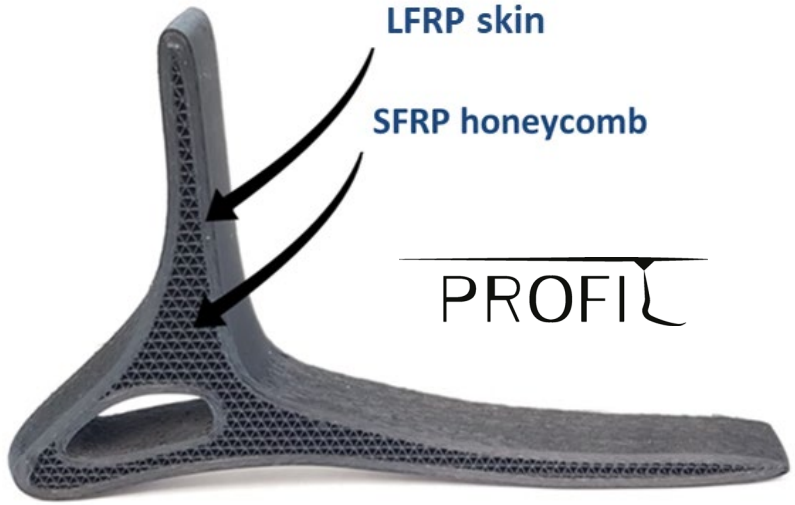
MOTIVATIONS

Benchmark: Laminated composite foot prosthesis

- ⊕ Lightweight
- ⊕ Excellent mechanical properties
- ⊖ Expensive
- ⊖ Low customization

3D printed: Sandwich like structure

- Continuos fibre skins
- Short fibre core



- ⊕ Lightweight
- ⊕ Good mechanical properties
- ⊕ Reduced cost
- ⊕ High tailorability
- Printing parameters performance dependent
- Safe and optimum design based on material characterization

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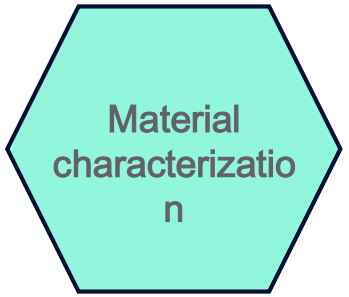
MATERIAL CHARACTERIZATION: CHALLANGES AND IMPORTANCE

What affects characterization?



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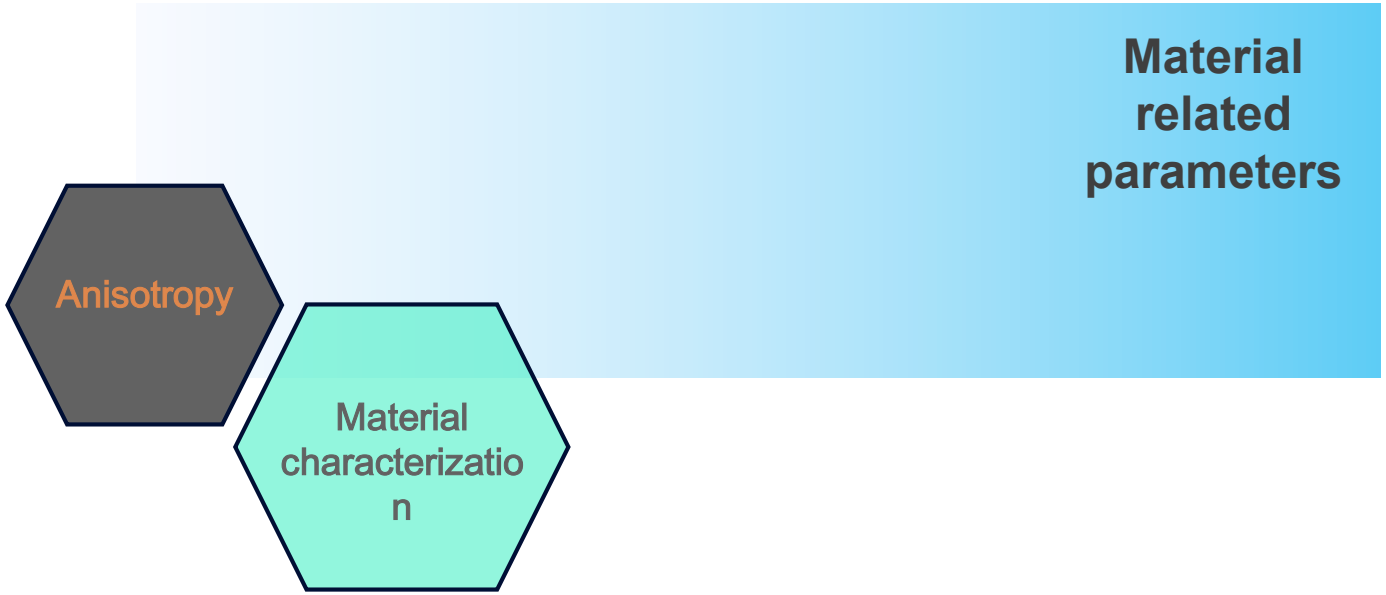

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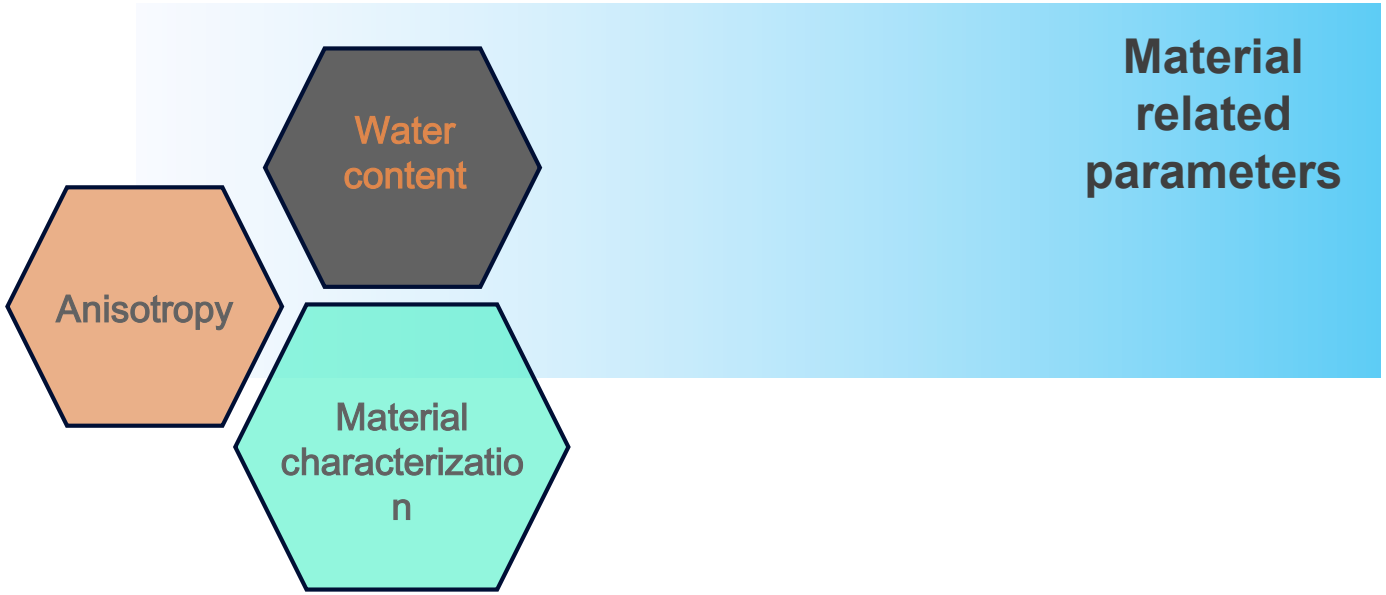

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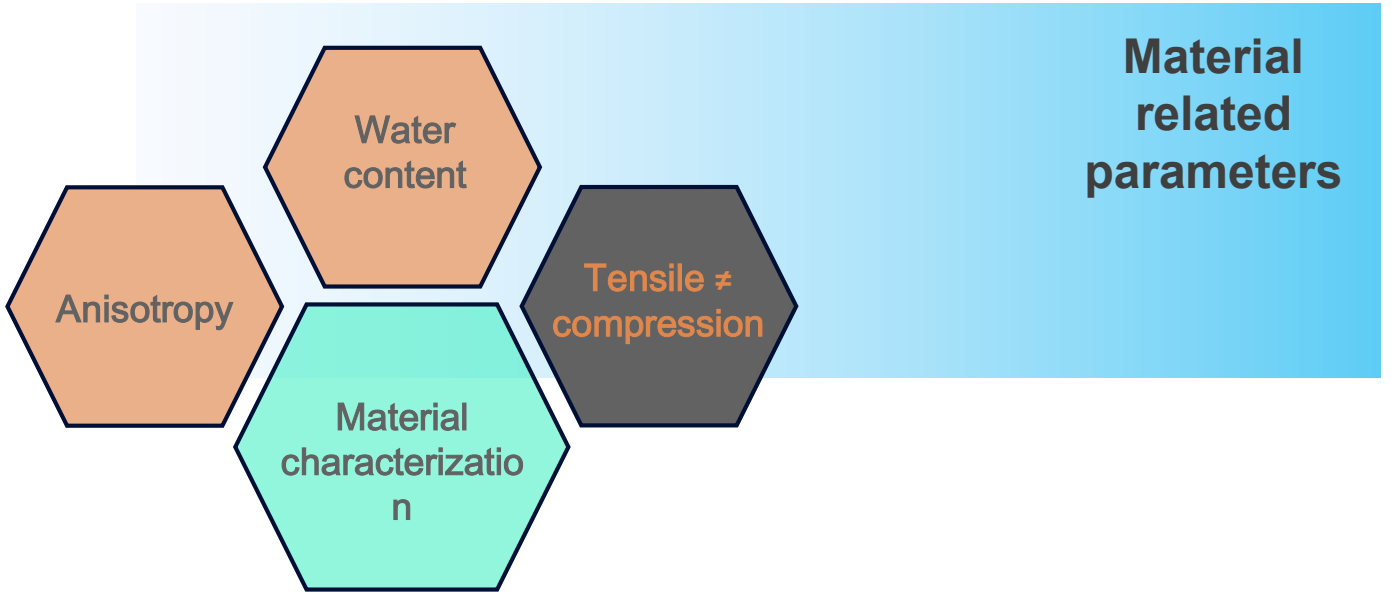

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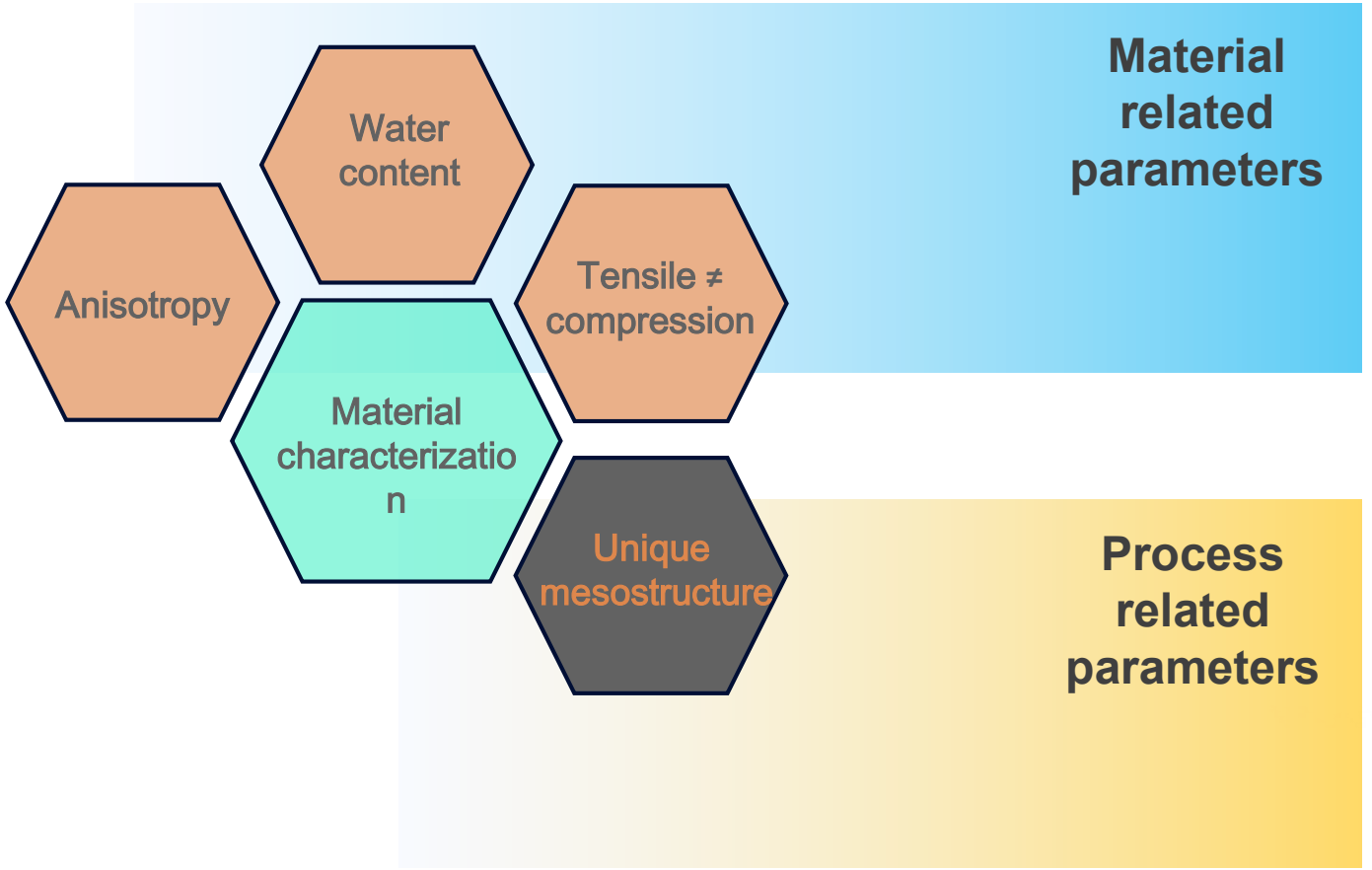

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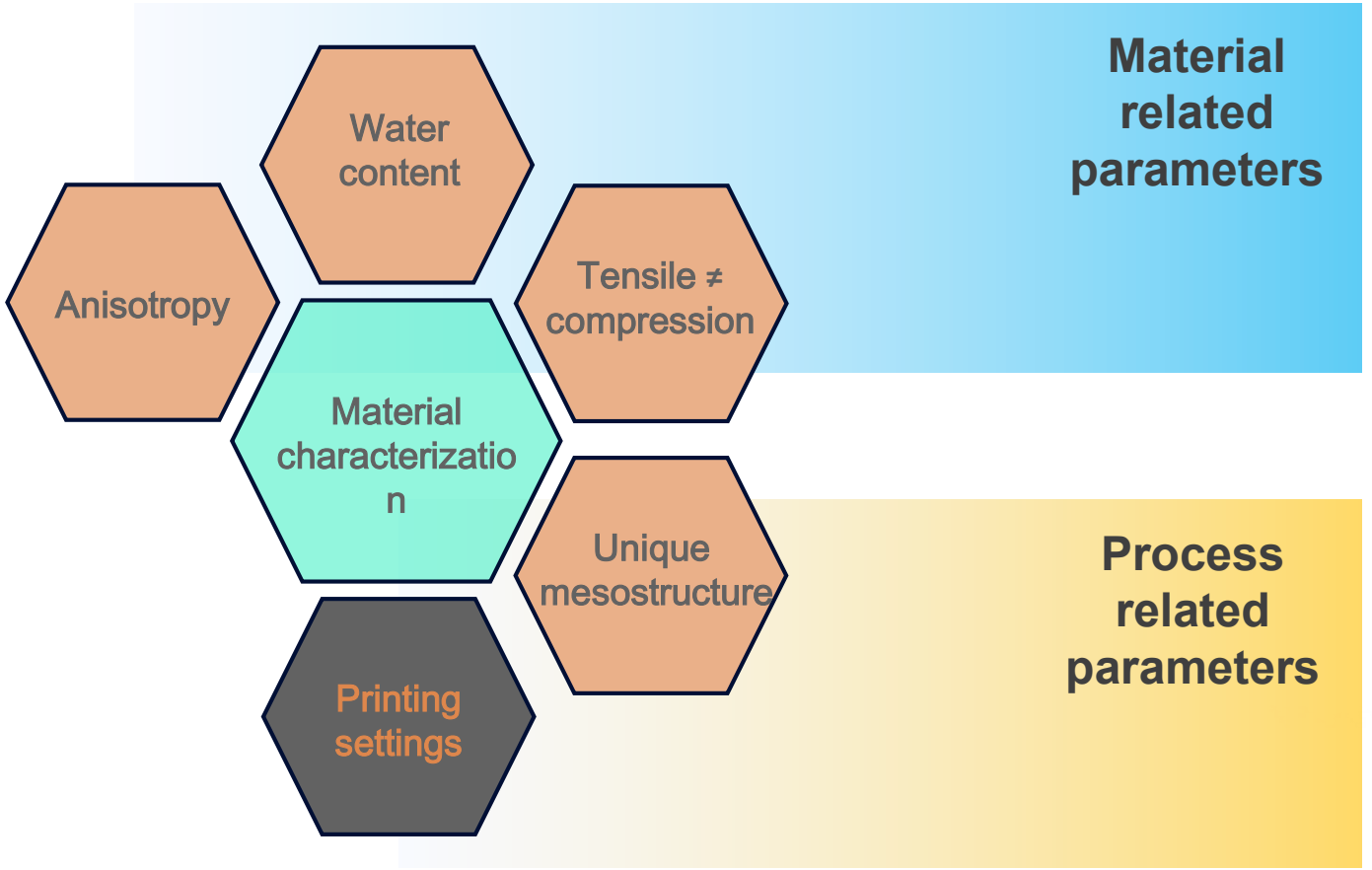

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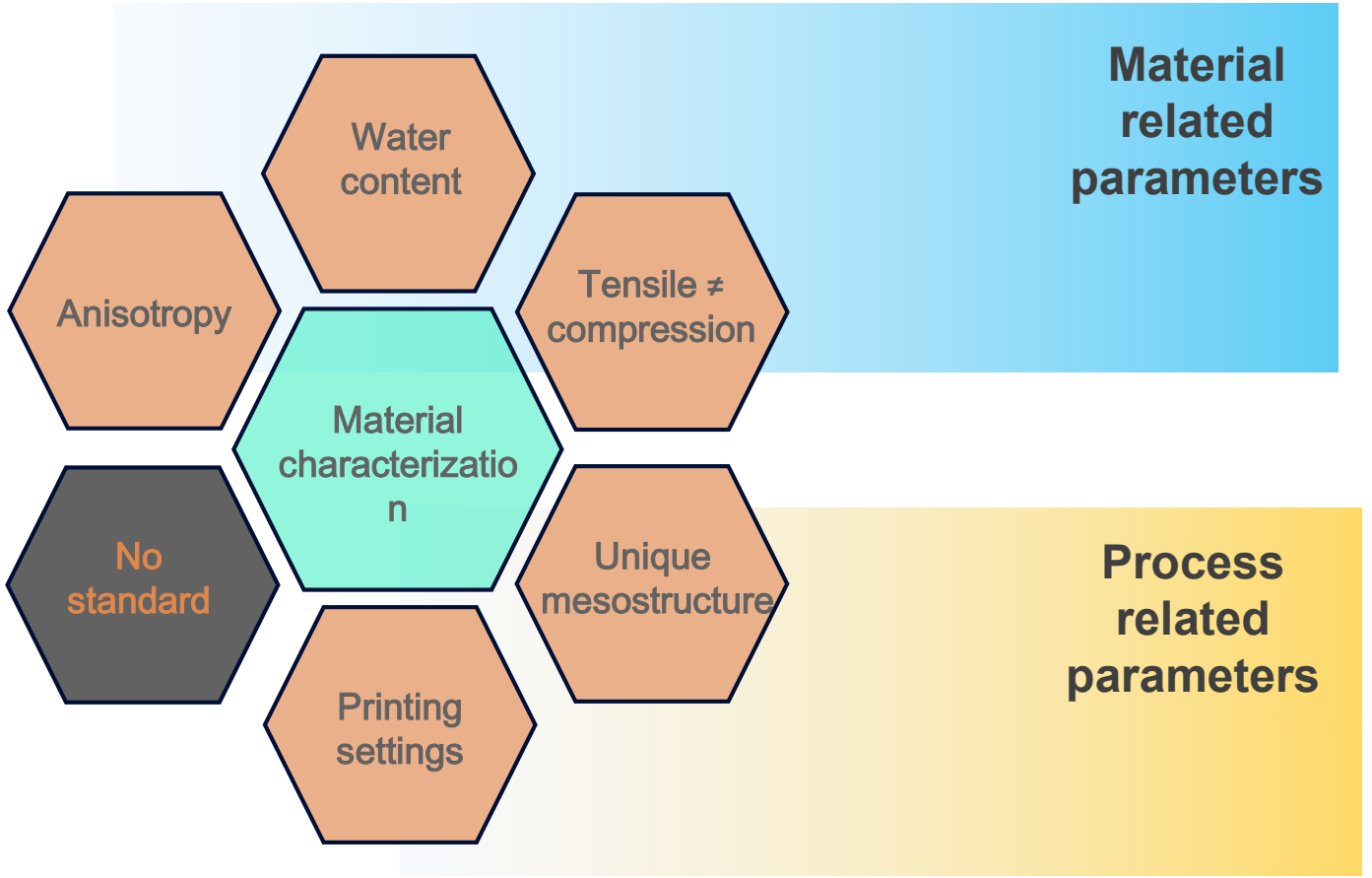
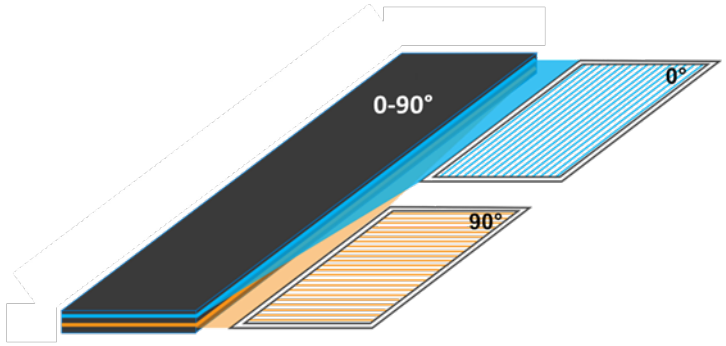


TENSILE CHARACTERIZATION

- **Material:** Micro-carbon fibre reinfroced PA6, supplied by Markforged (Onyx TM)
- **Specimen:** 0-90° layers stacking sequence



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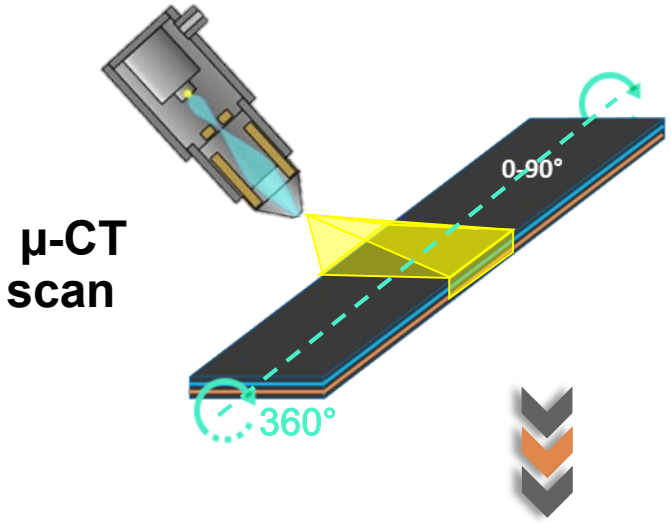
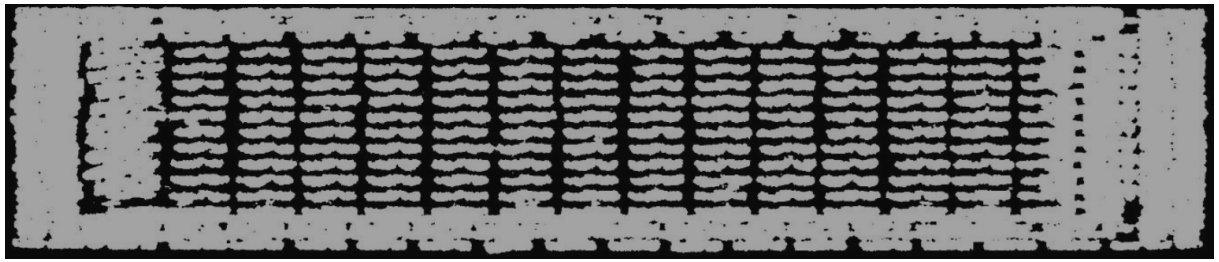


Meso-structure morphology of specimen's cross-section



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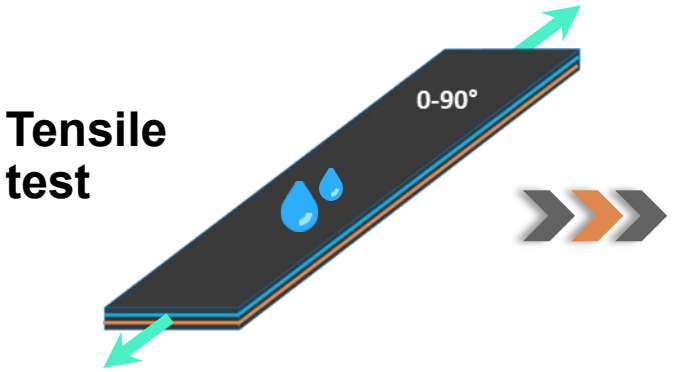

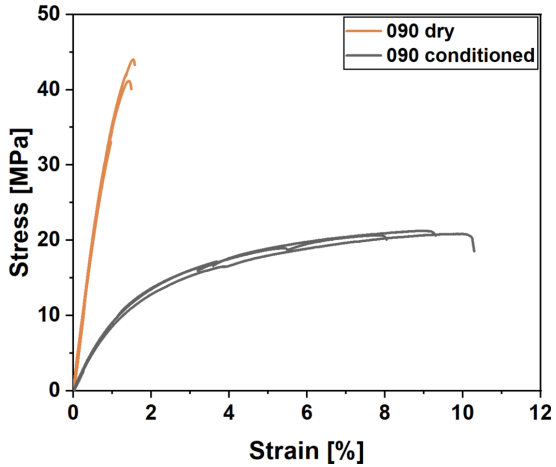

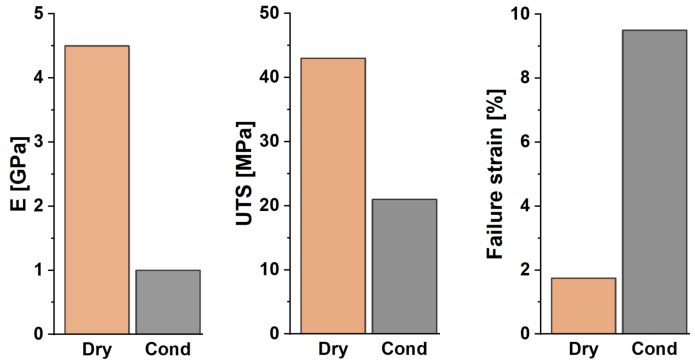

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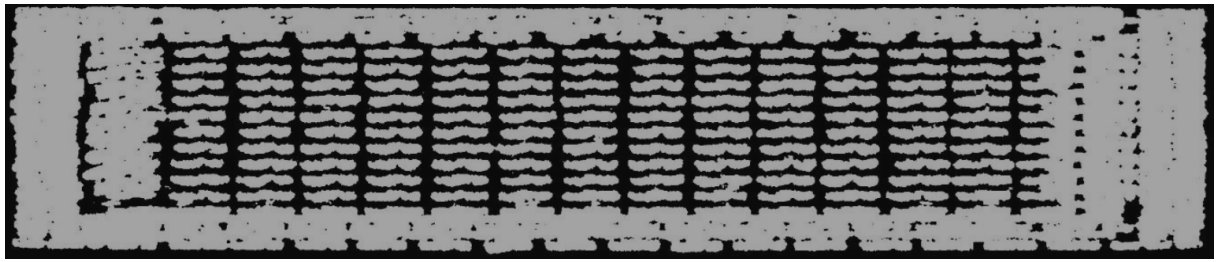

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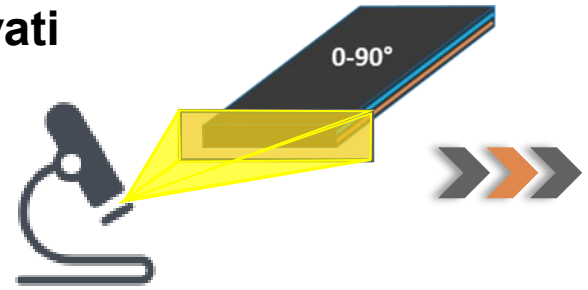
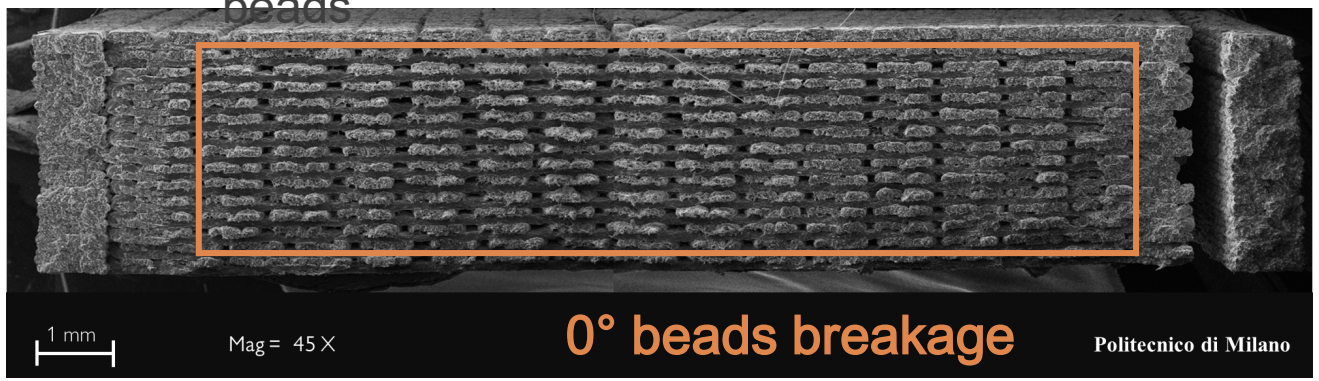


Failure surface perpendicular to the 0° beads



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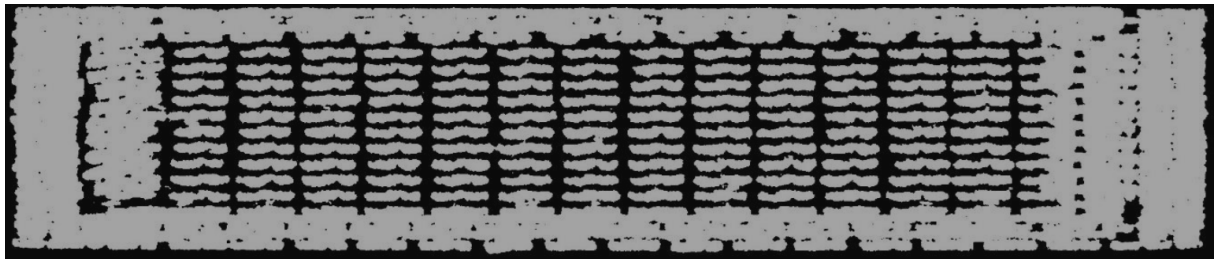

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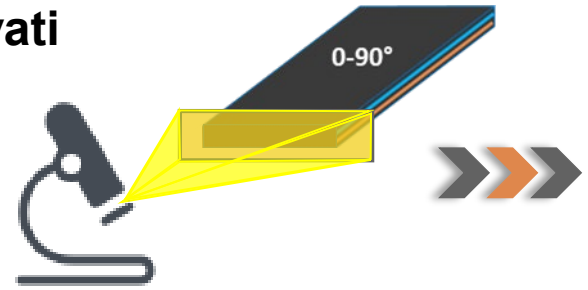

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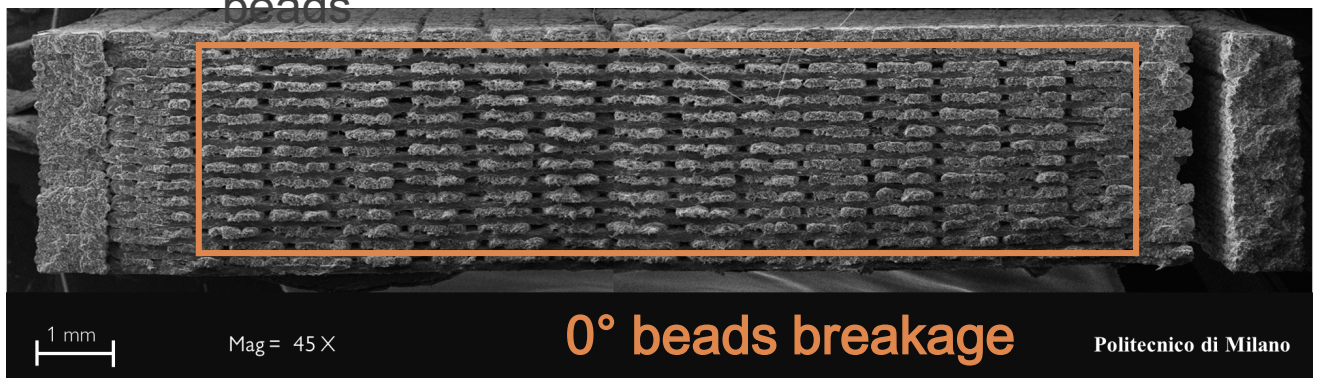

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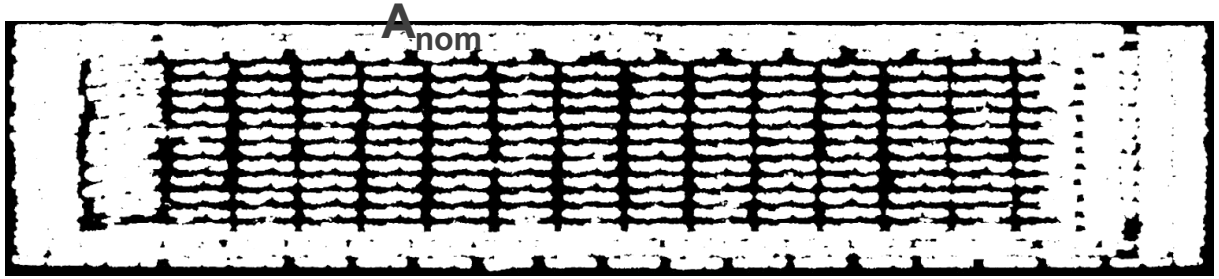
$A_{eff} \sim 65\% A_{nom}$



- **Material properties could be underestimated**
- **Water largely affects all properties**

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COMPRESSIVE CHARACTERIZATION

- **Material:** Micro-carbon fibre reinfroced PA6, supplied by Markforged (Onyx TM)
- **Specimen:** small specimens for **Longitudinal** and **Transverse** properties evaluation
- **Design:** avoid **buckling** and limit **barreling**

UD specimens made up of concentric contour beads only

COMPRESSIVE CHARACTERIZATION

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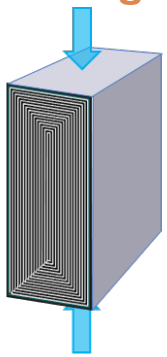
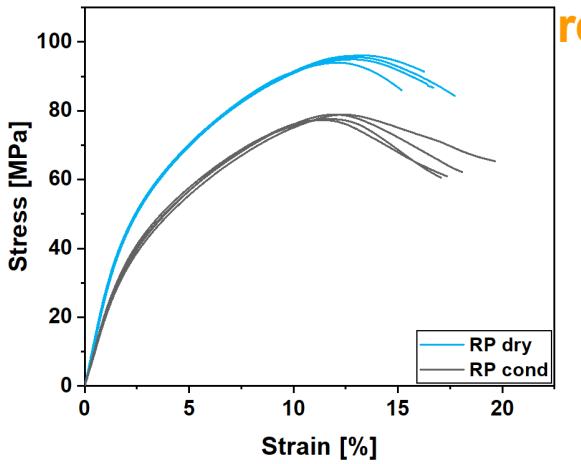
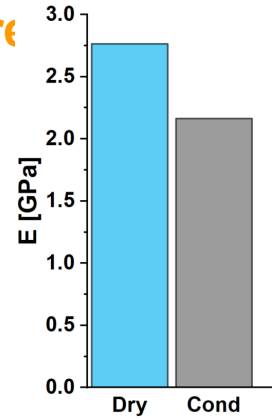
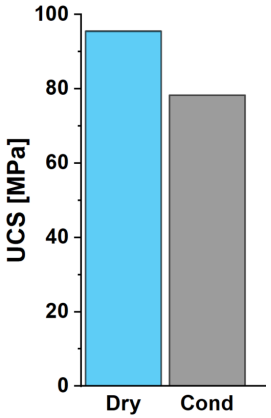
- **Design:** av

RP









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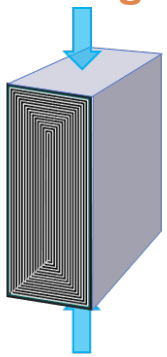
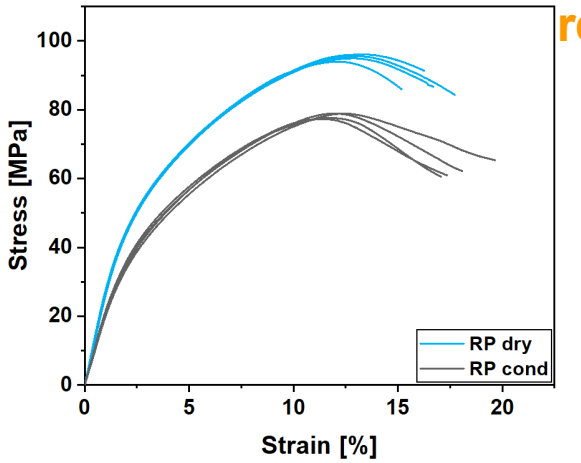
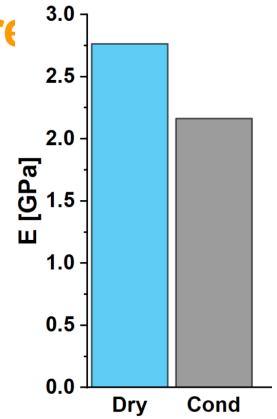
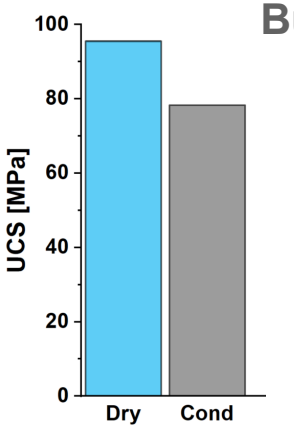
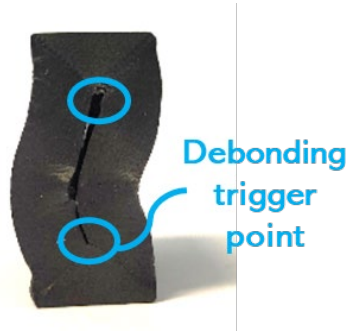








Buckling delamination



- E_L evaluated
- Ucs lower bound
- 20% reduction E, UCS due to water

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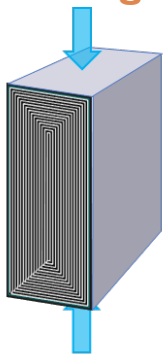

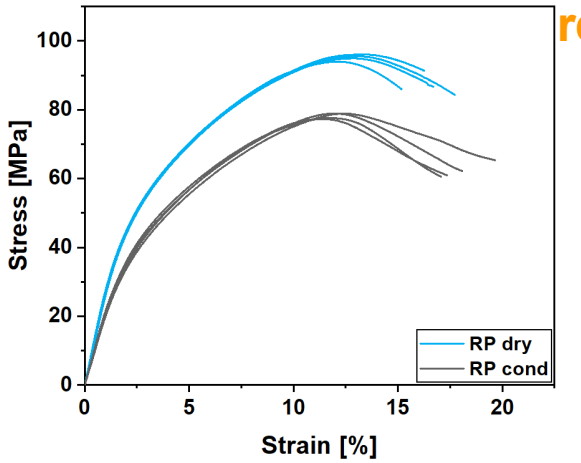

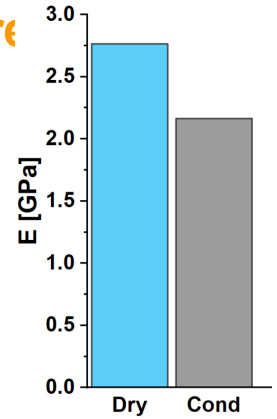

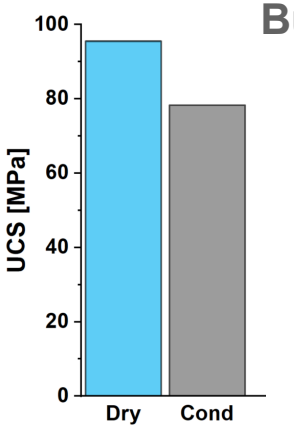

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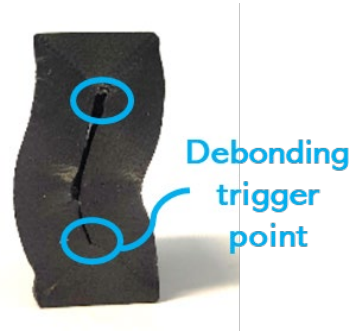

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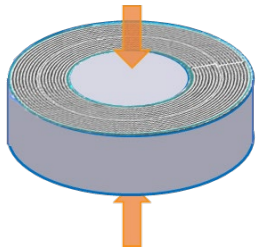
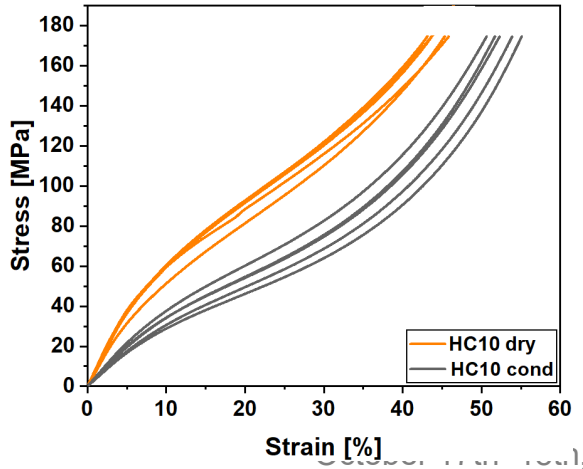
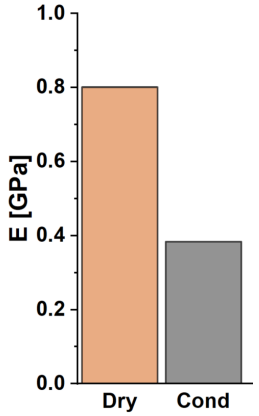
HC10







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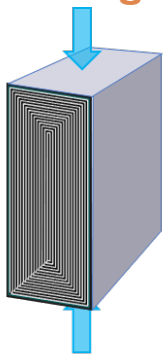

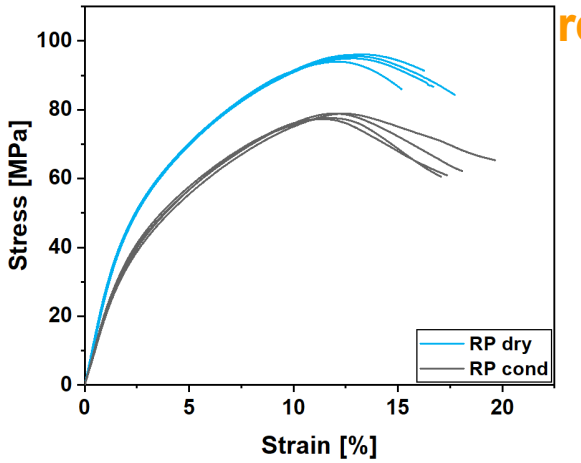

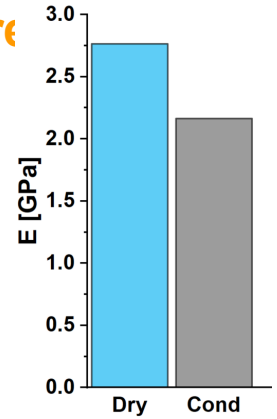

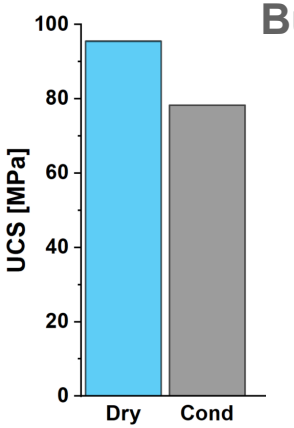

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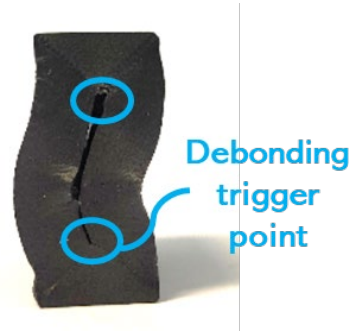

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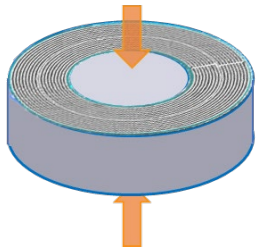
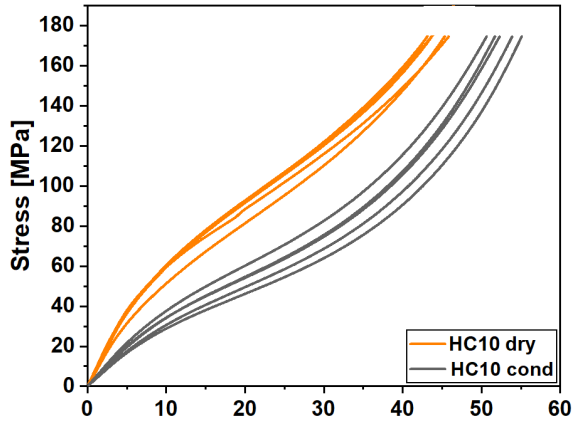
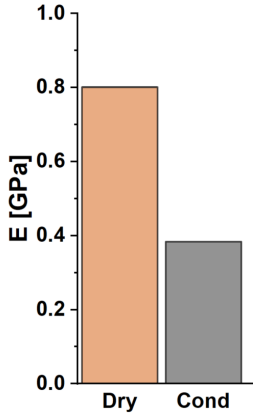






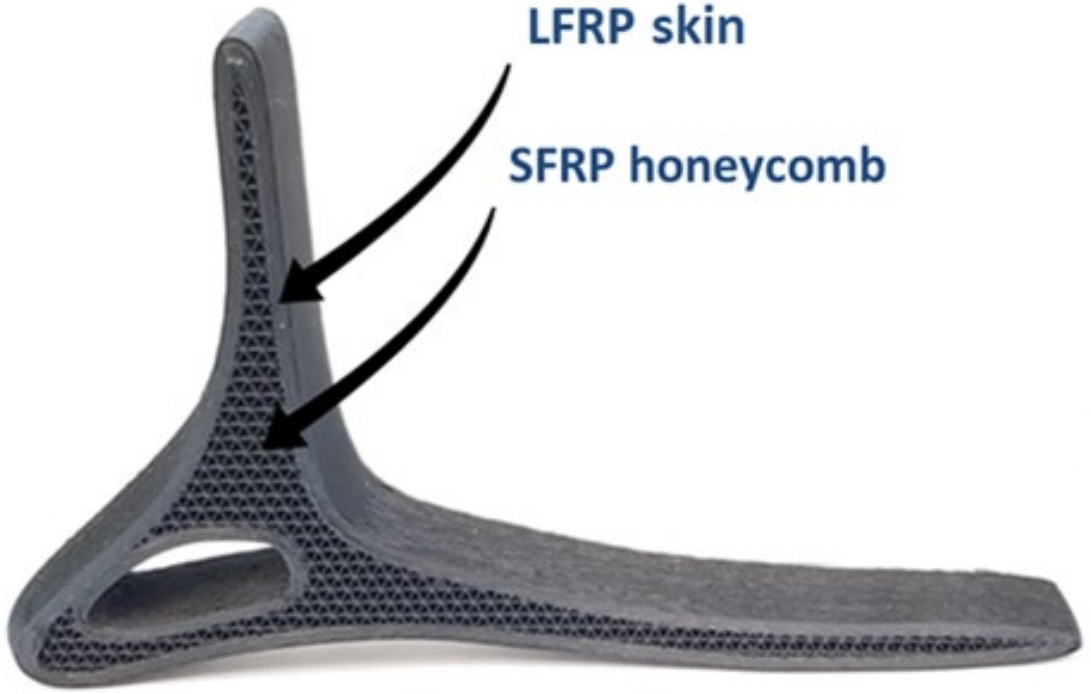
Convex barreling

Concave barreling

- E_C evaluated
- Water affects barreling
- 50% reduction E, due to water

MOTIVATIONS

3D printed composite foot prosthesis



- Lightweight
- Good mechanical properties

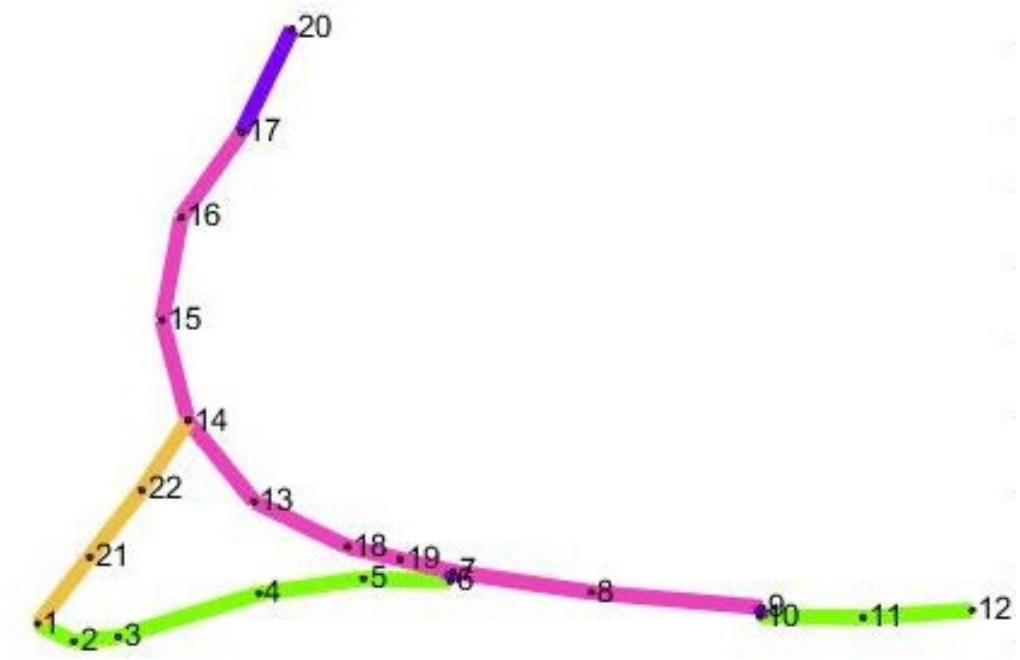
- Reduced cost
- Increased customisation

Geometry versatility

Too many parameters

MOTIVATIONS

Development of a 2D design and optimisation tool



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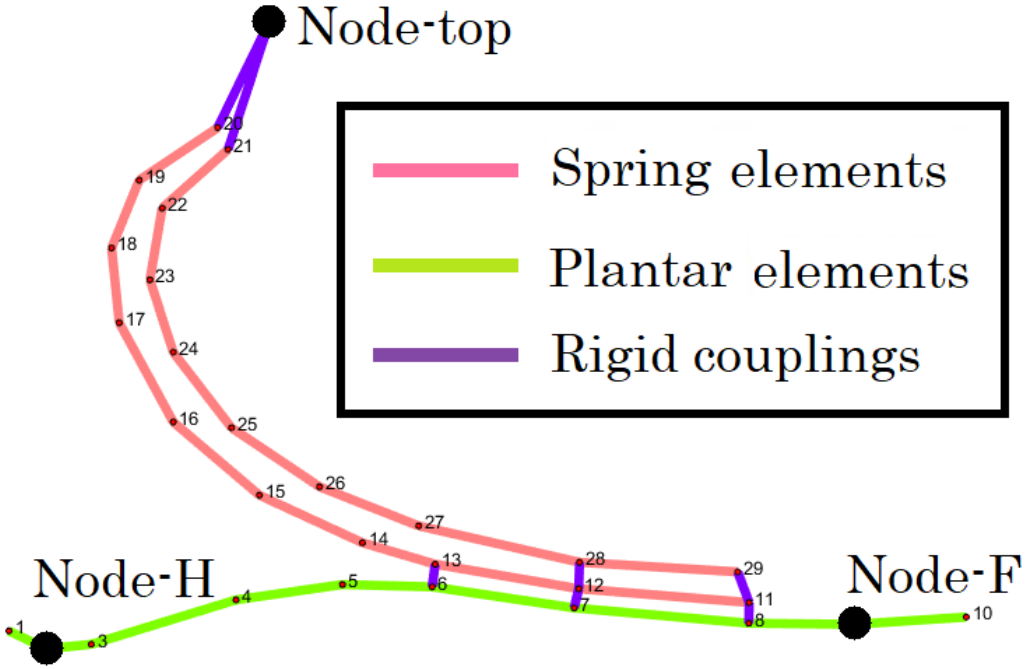
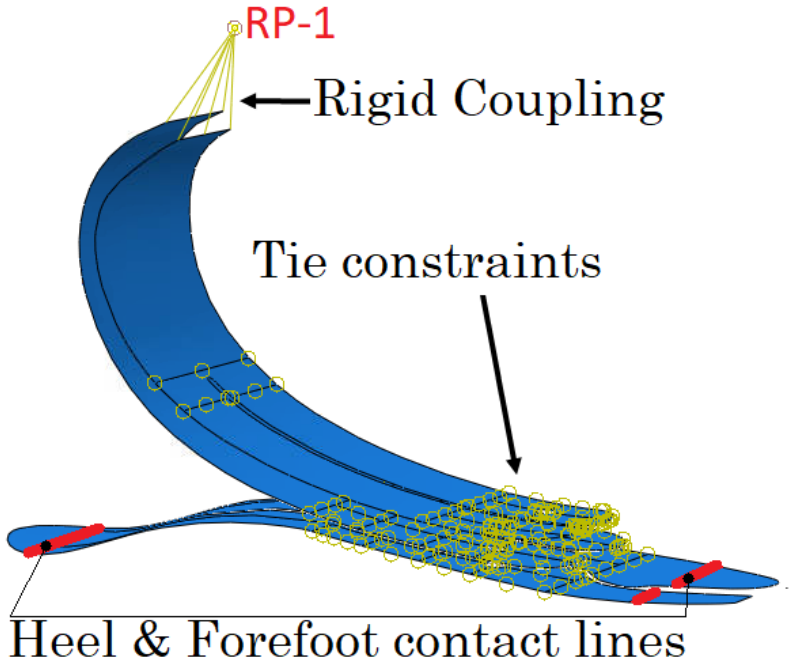
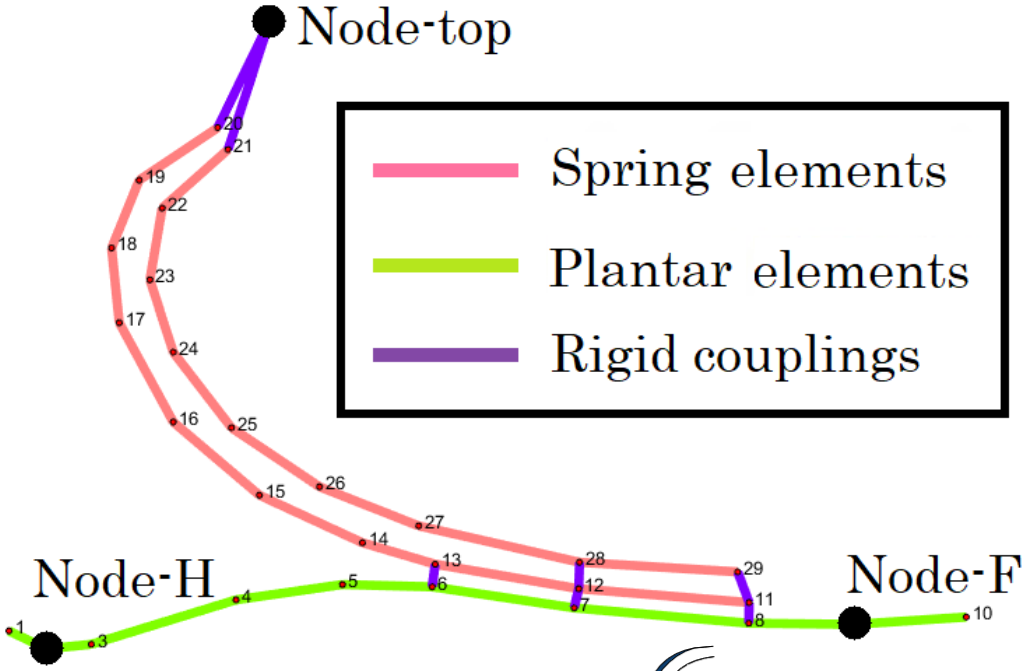
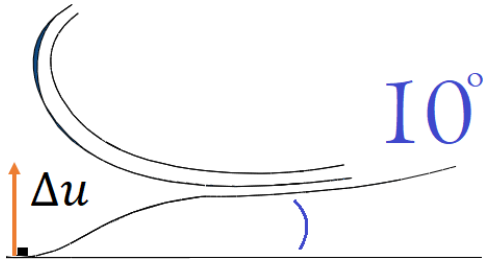
VALIDATION OF THE 2D OPTIMISATION TOOL



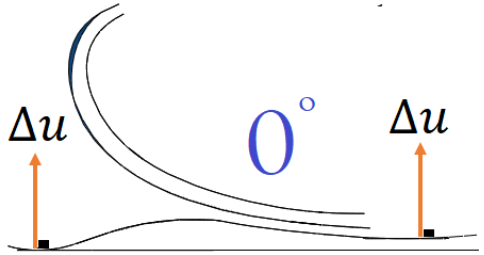
VALIDATION OF THE 2D OPTIMISATION TOOL



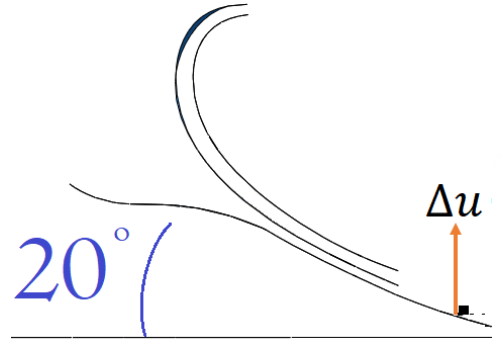




Heel-strike

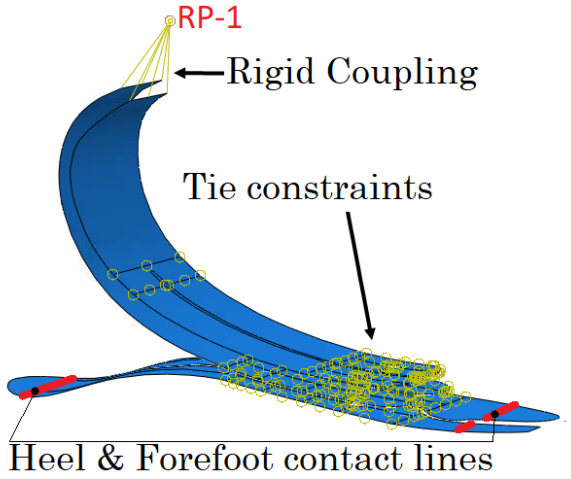


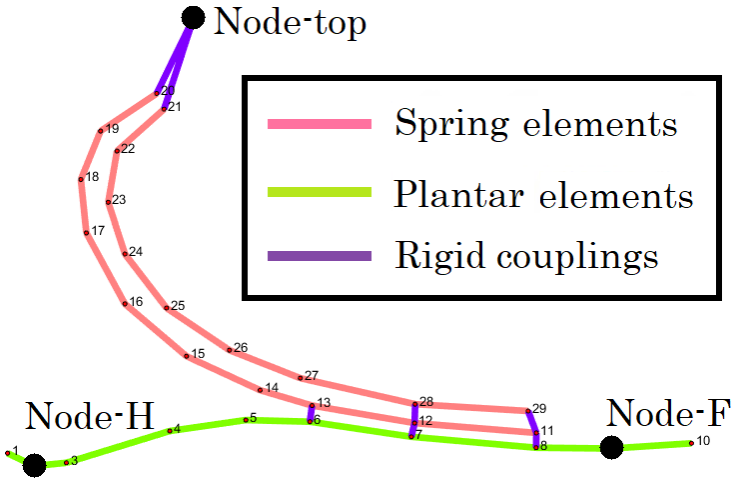
Mid-stance

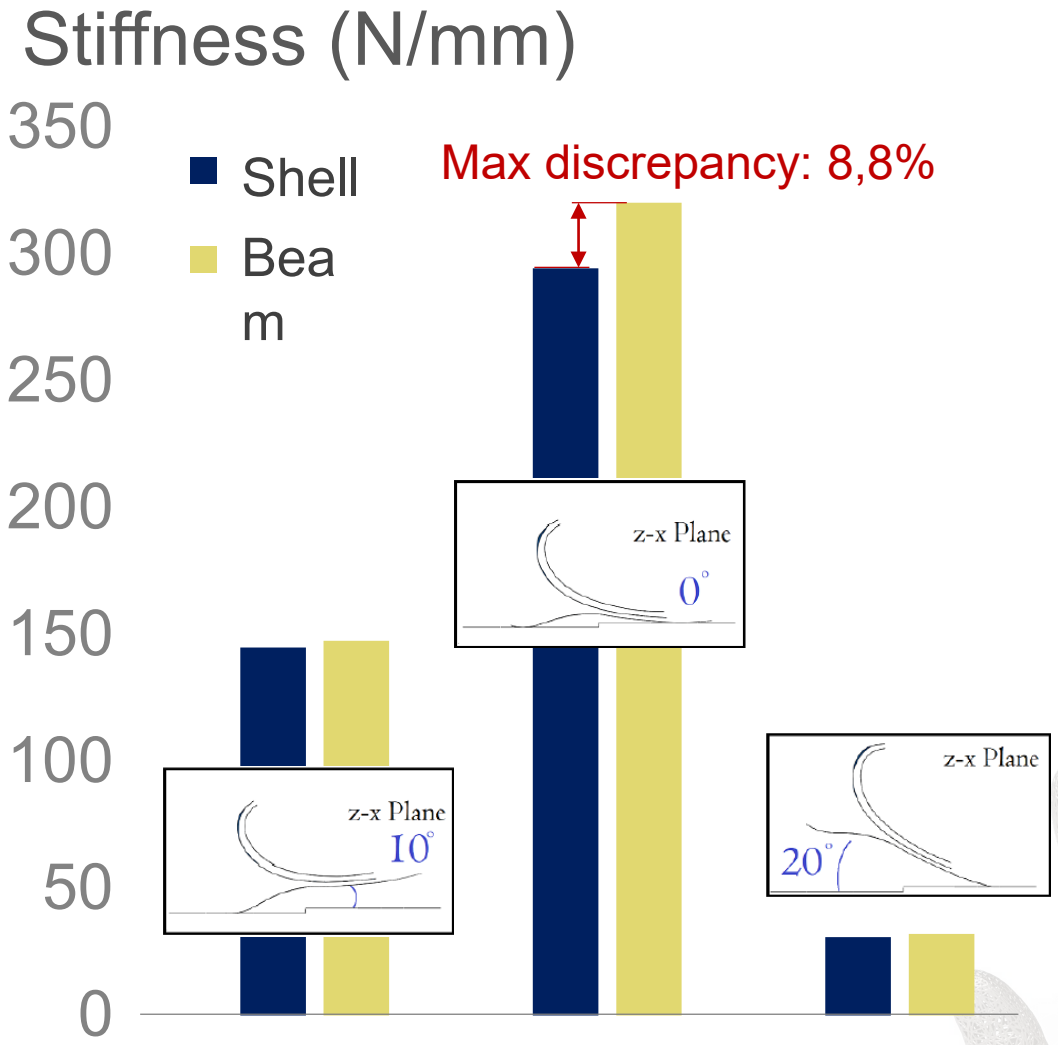


Toe-off

VALIDATION OF THE 2D OPTIMISATION TOOL





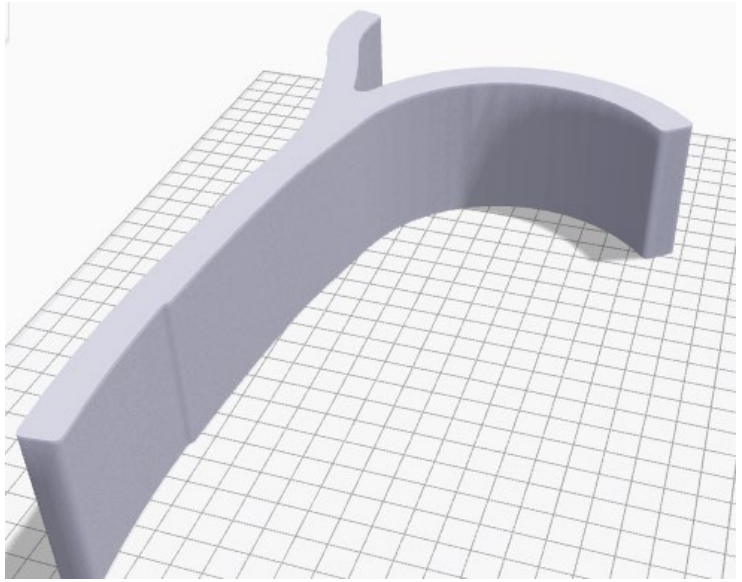


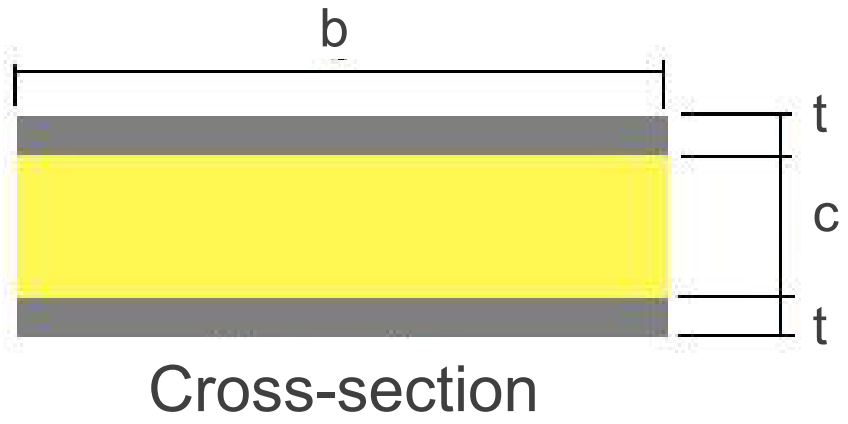
ADDITIVE 4 BIOMEDICAL

APPLICATION TO 3D PRINTED PROSTHESIS

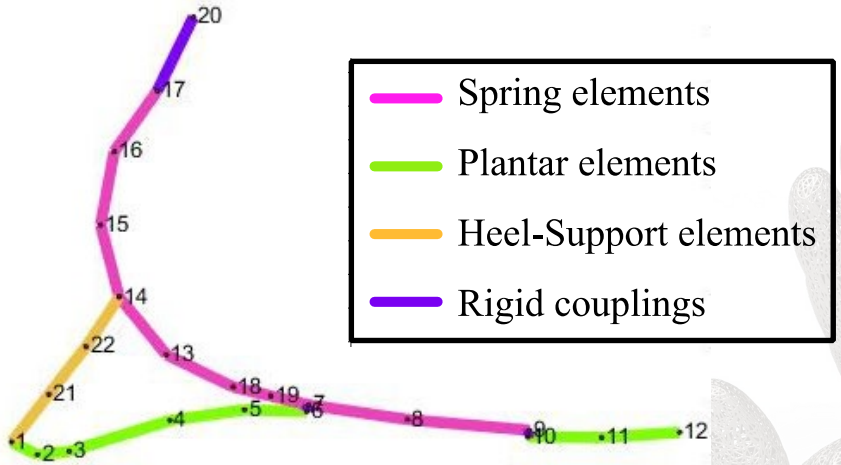
Improvement by AM:

- Integrated structure
- Sandwich-like cross-sections





Cross-section



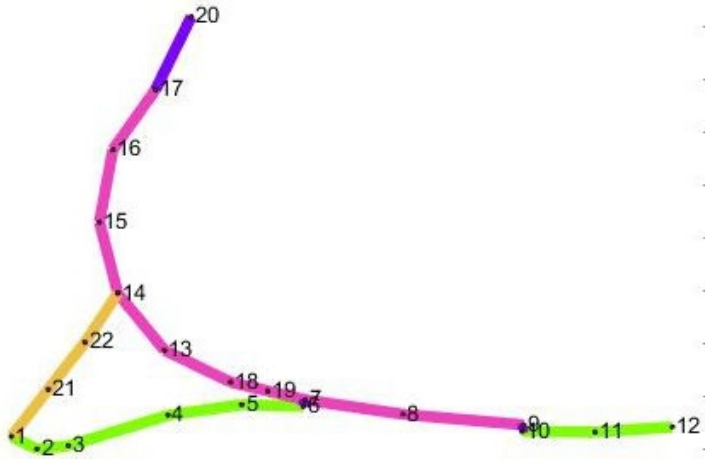
NEW CONFIGURATIONS

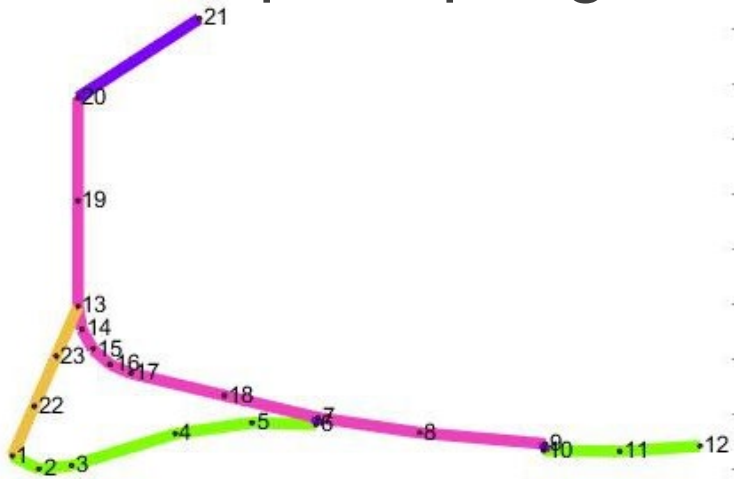
ADDITIVE 4 BIOMEDICAL

C-shaped spring

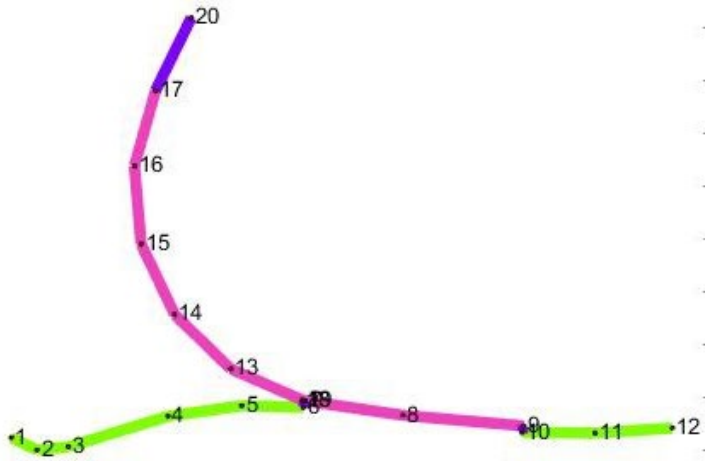
J-shaped spring

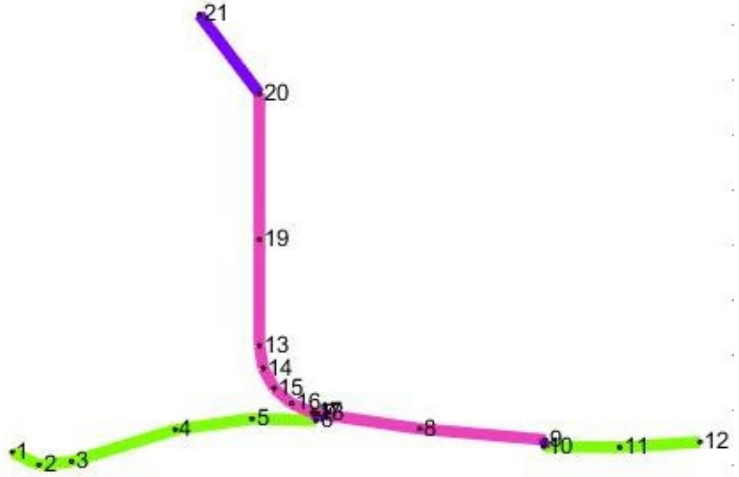
Heel support





No heel support





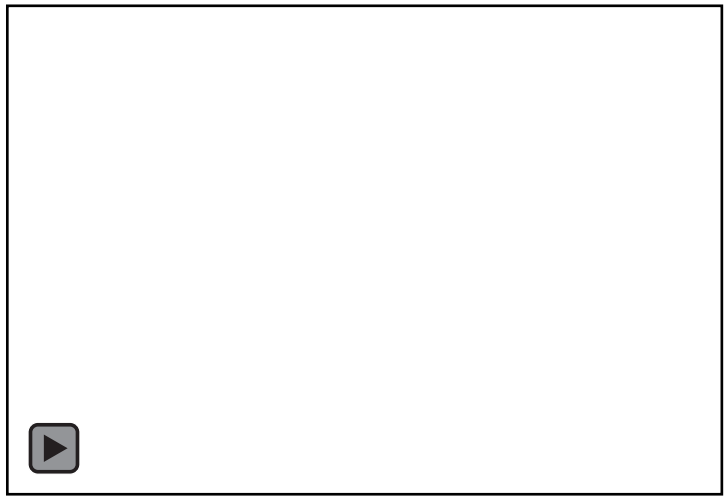
NEW CONFIGURATIONS

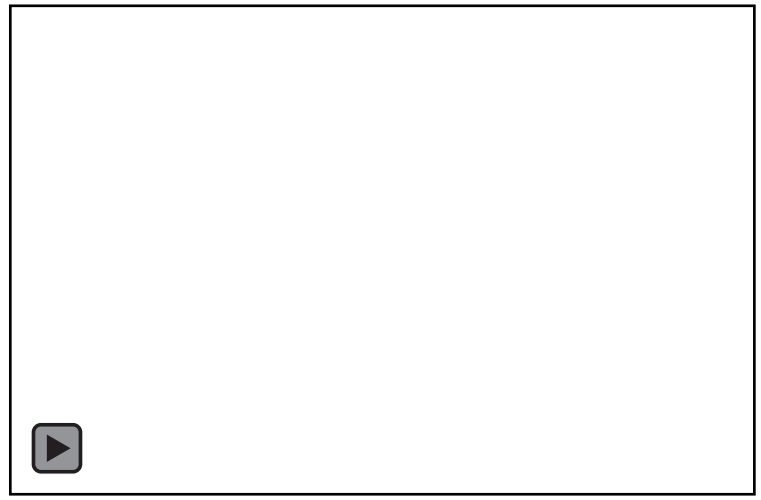
C-shaped spring

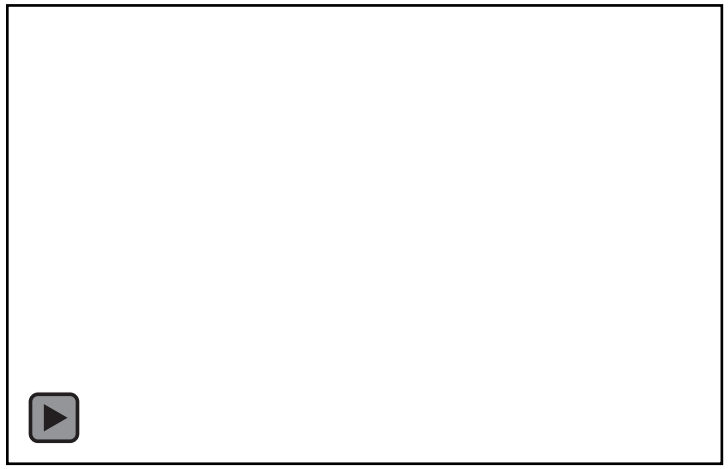
J-shaped spring

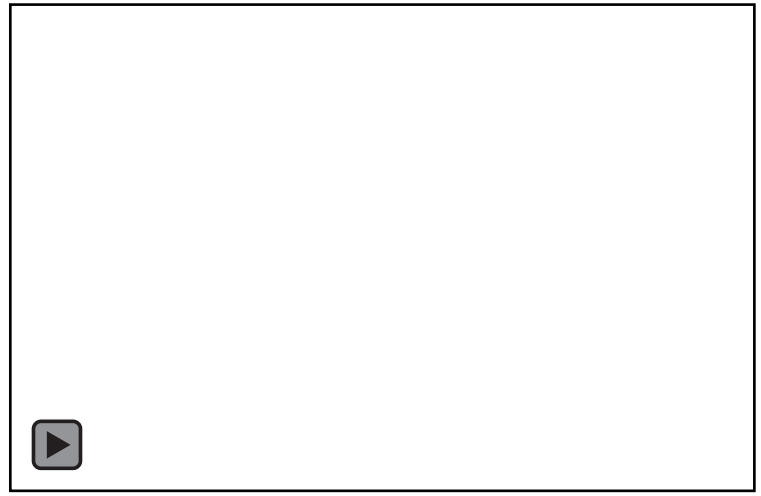
Heel support

No heel support





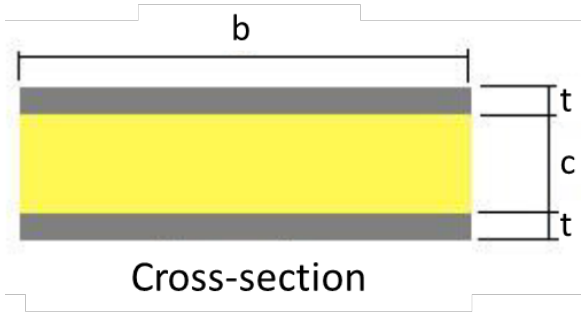




ADDITIVE 4 BIOMEDICAL

APPLICATION TO 3D PRINTED PROSTHESIS

Material structure optimisation

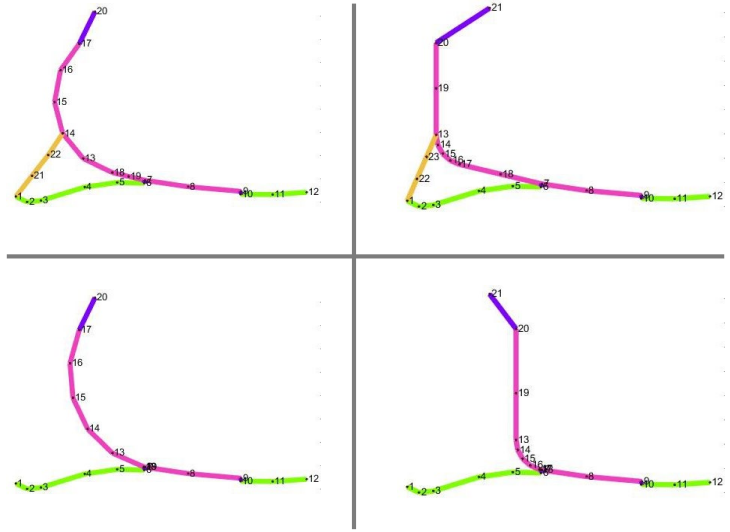


Spring b, c, t

Plantar b, 0.75 c, t

Heel b, 0.5 c, t

Geometry optimisation



Design variables: c, t and config. #

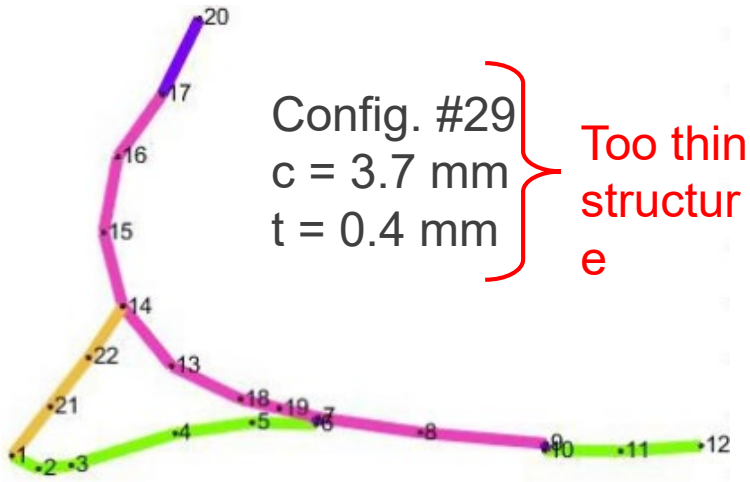
Design constraint: same stiffness of the reference prosthesis

Objective function: minimise weight

NEW CONFIGURATIONS

C-shaped spring

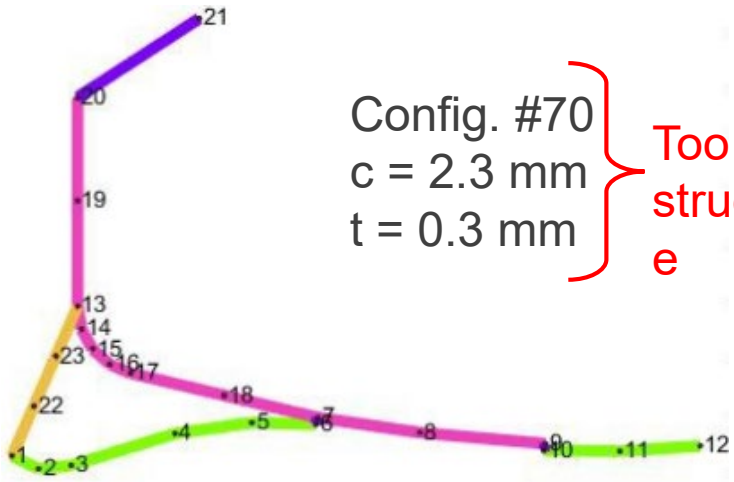
Heel support



Config. #29
c = 3.7 mm
t = 0.4 mm

Too thin structure

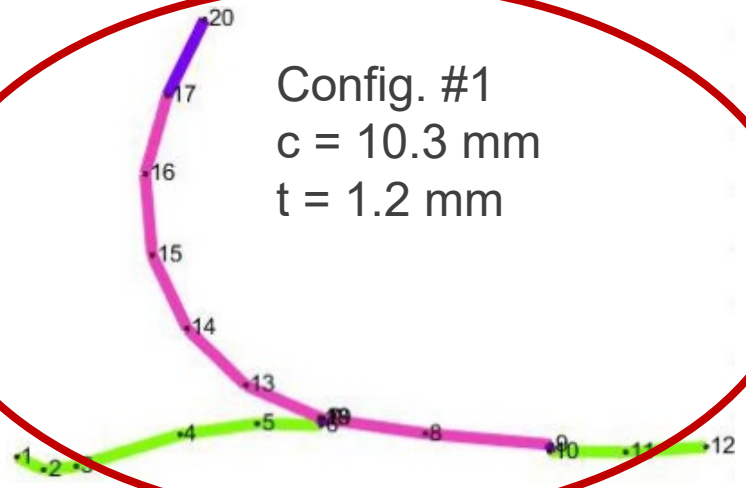
J-shaped spring



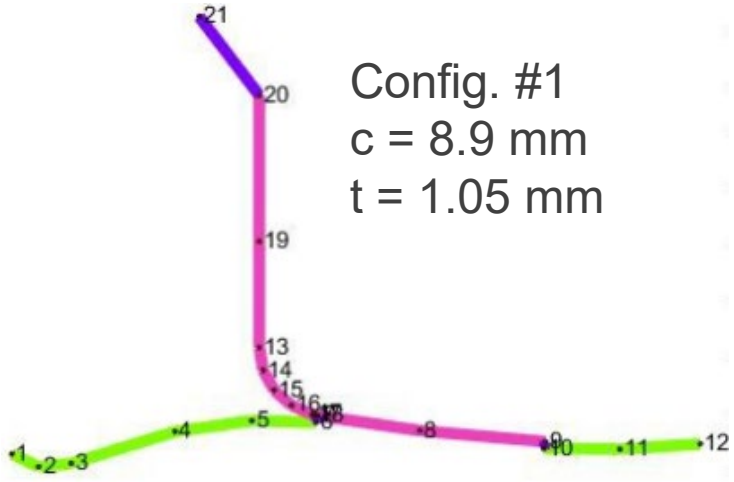
Config. #70
c = 2.3 mm
t = 0.3 mm

Too thin structure

No heel support



Config. #1
c = 10.3 mm
t = 1.2 mm

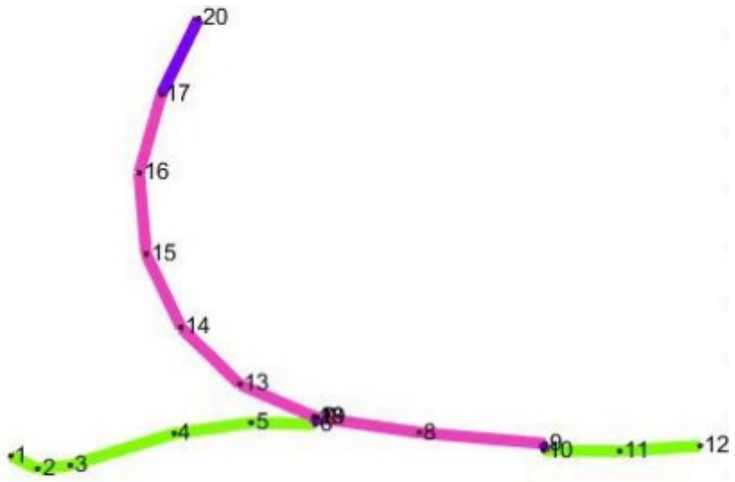


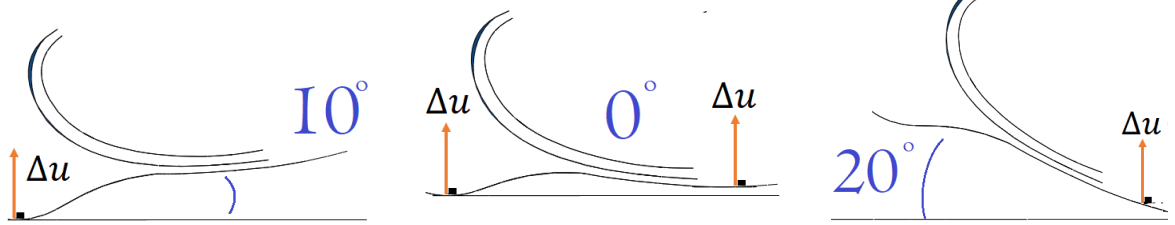
Config. #1
c = 8.9 mm
t = 1.05 mm

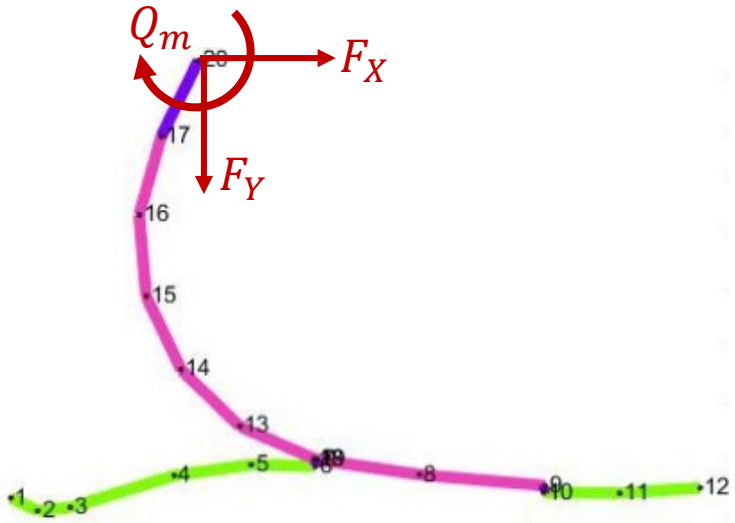
ADDITIVE 4 BIOMEDICAL

CoCo AM Additive Manufacturing SC 09/A3

DESIGN CASES





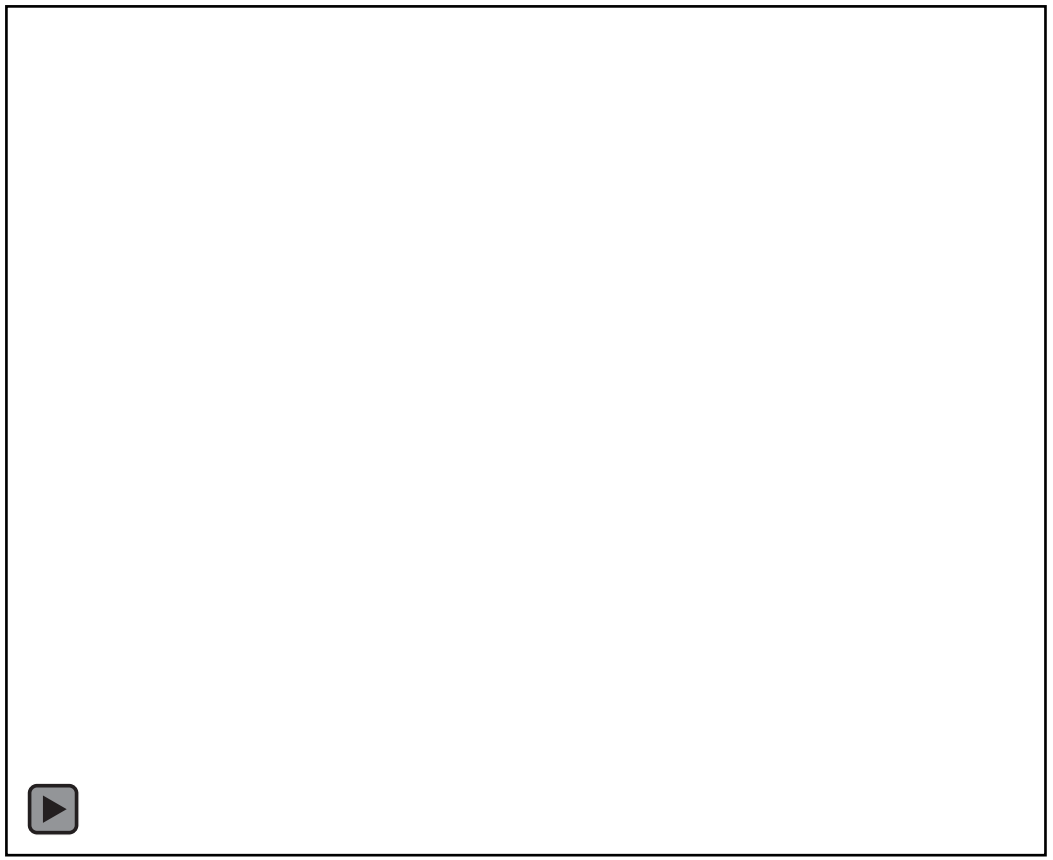


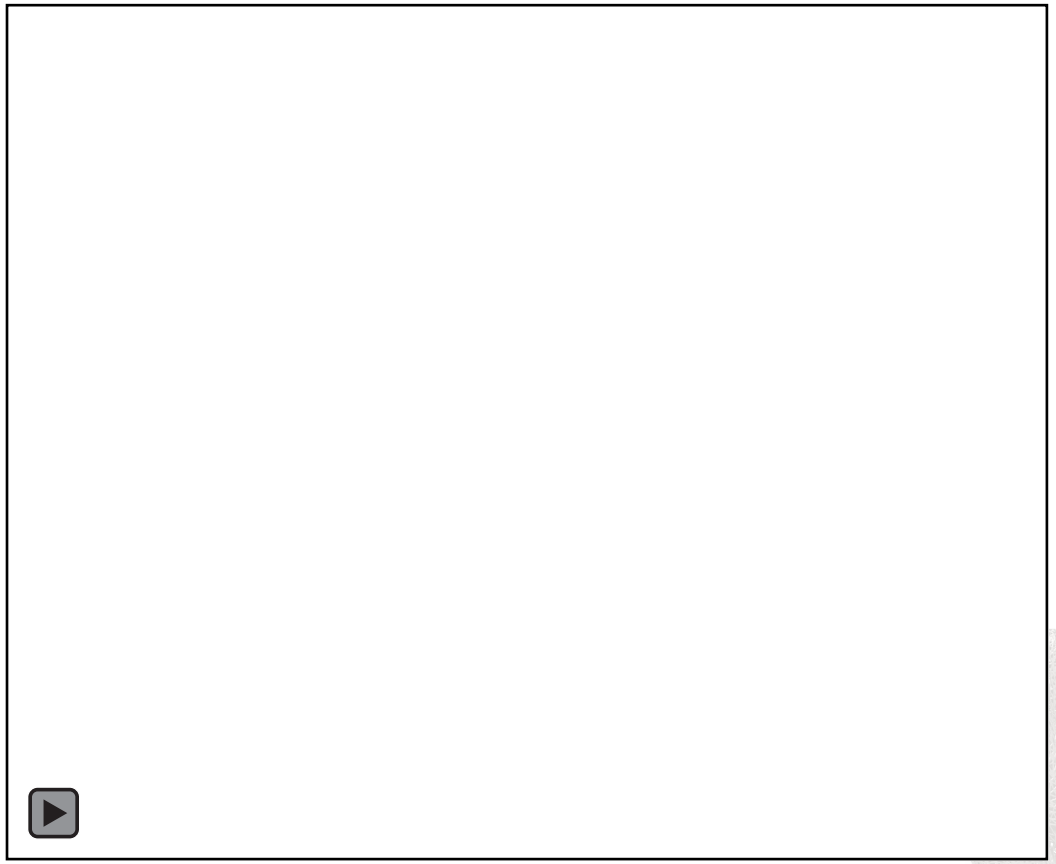
Design constraints:
- Heel-strike stiffness as reference
- Mid-stance stiffness as reference
- Tow-off stiffness as reference

Design constraints:
- Horizontal stiffness as referen
- Vertical stiffness as reference
- Transmitted torque to the pylo

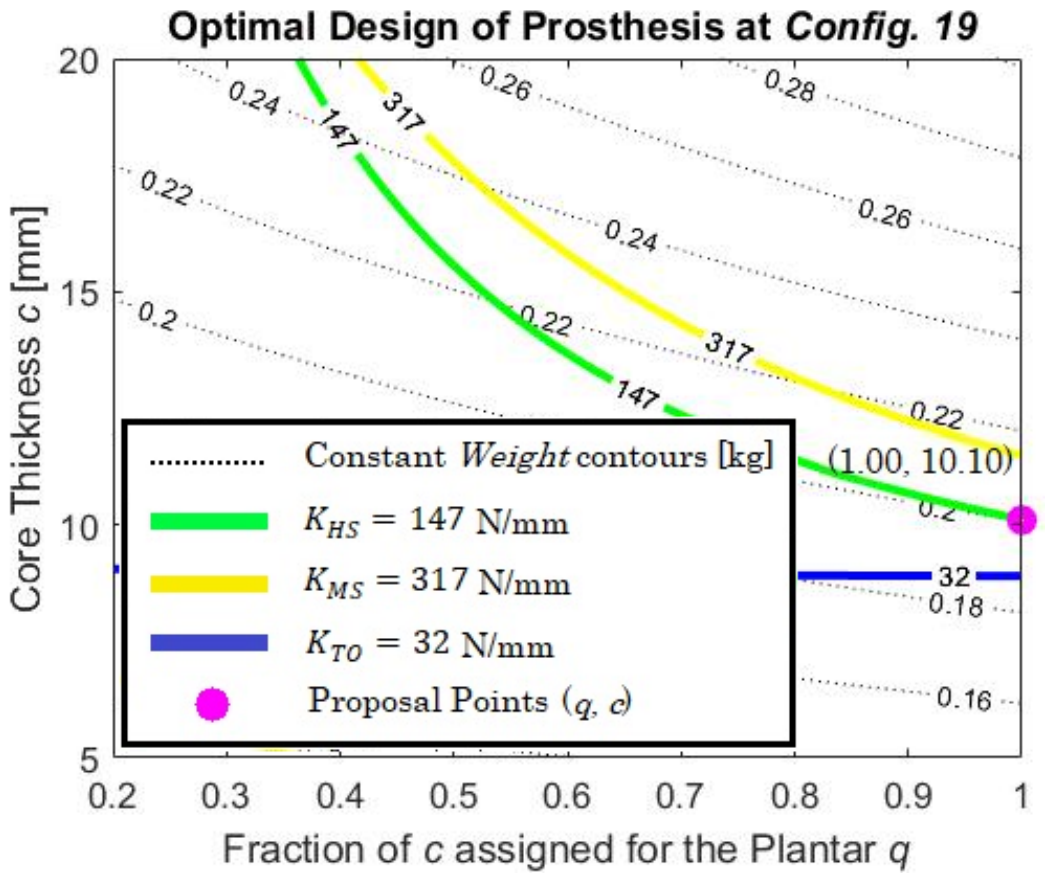
Design variables:
- **Configuration**
- **Core thickness plan Skin thickness = 0.9 mm**
- **Core thickness Spring**

DESIGN CASES

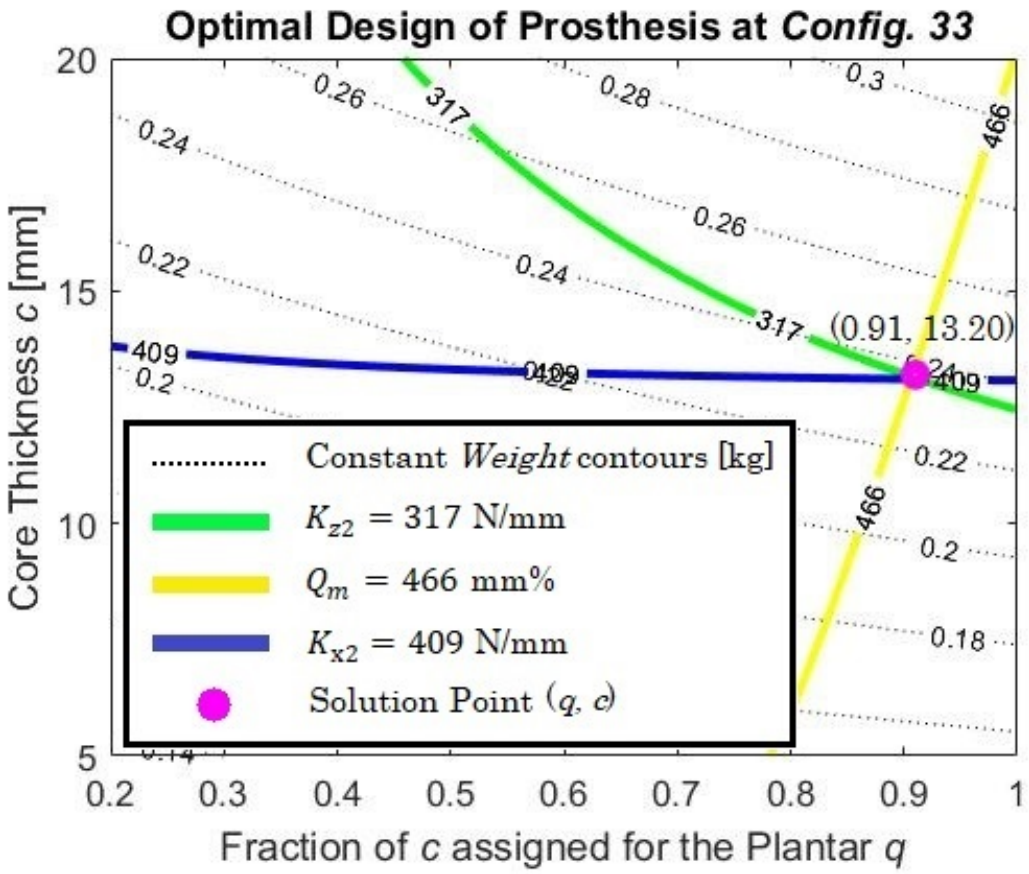




DESIGN CASES



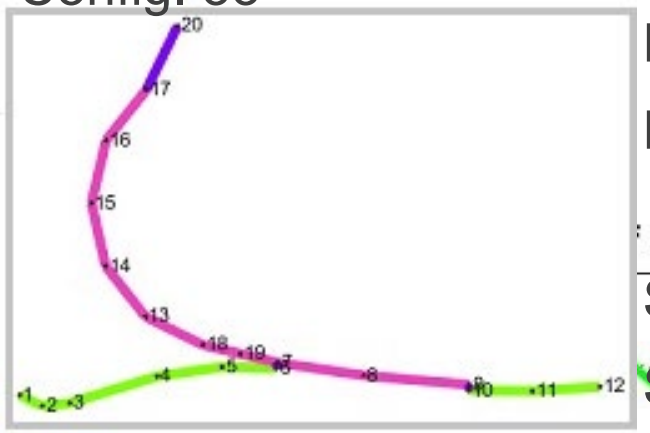
Solution does not exist



Solution exists

REFINED OPTIMISATIONS

Config. 33

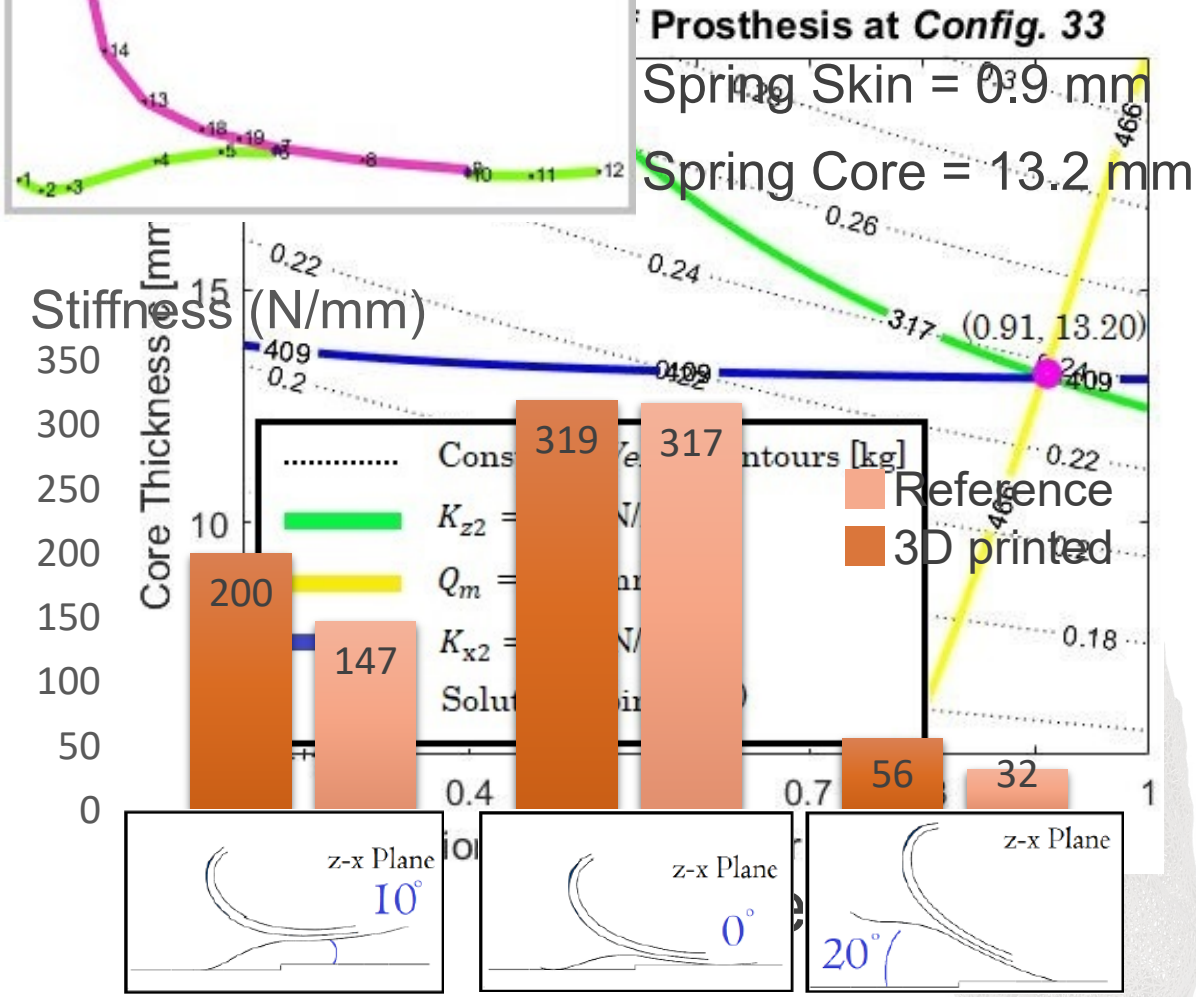


Plantar Skin = 0.9 mm

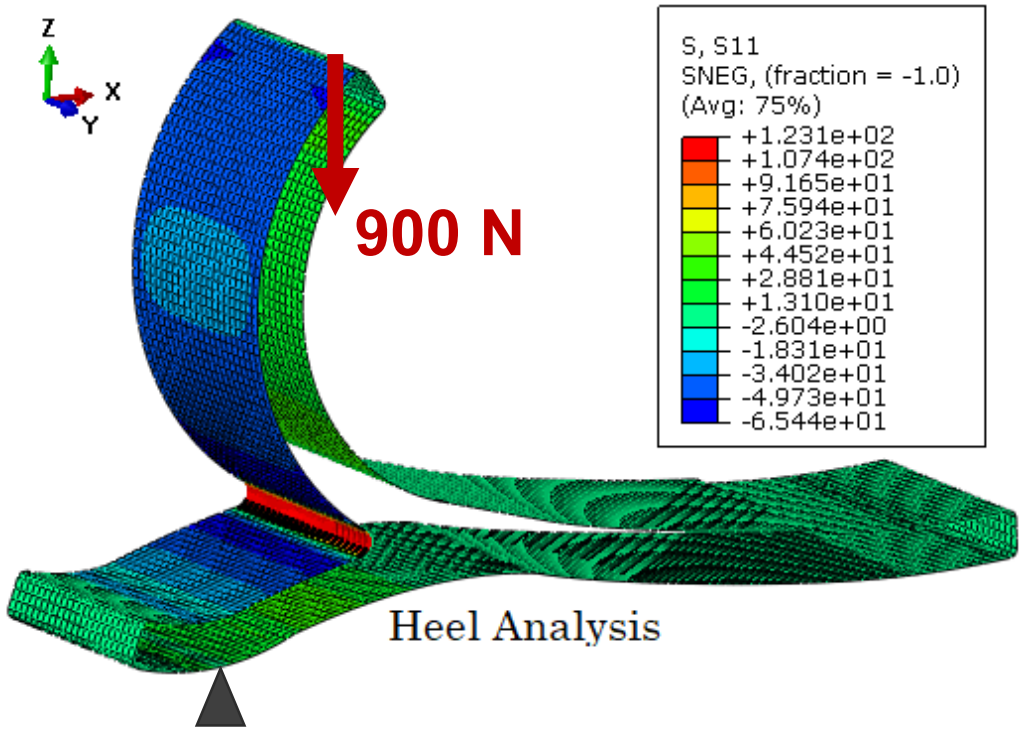
Plantar Core = 12 mm

Spring Skin = 0.9 mm

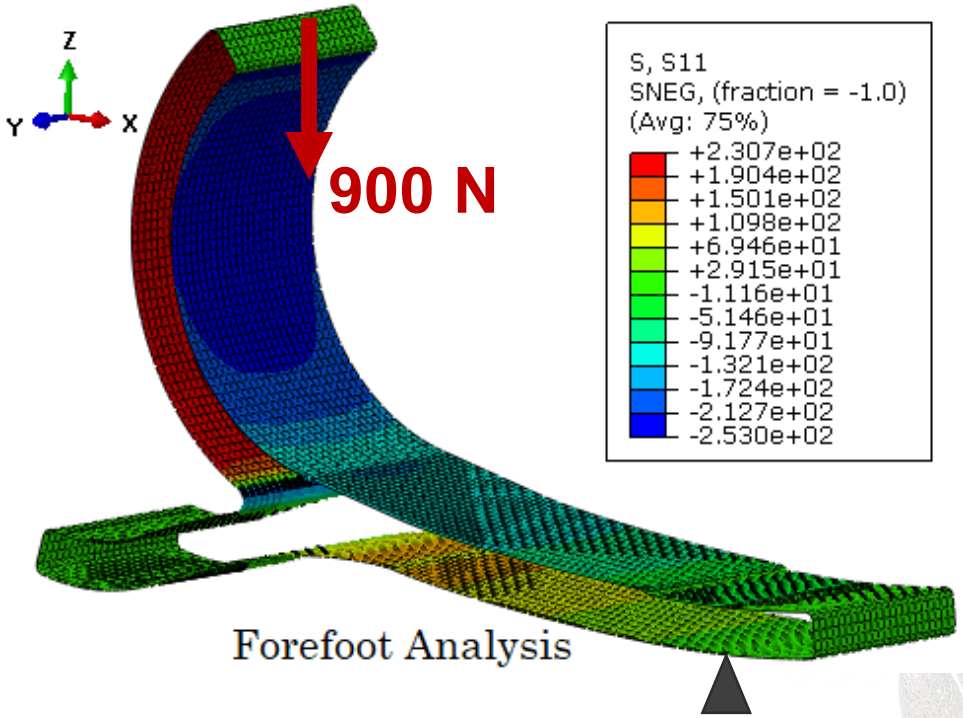
Spring Core = 13.2 mm



3D STRESS ANALYSIS

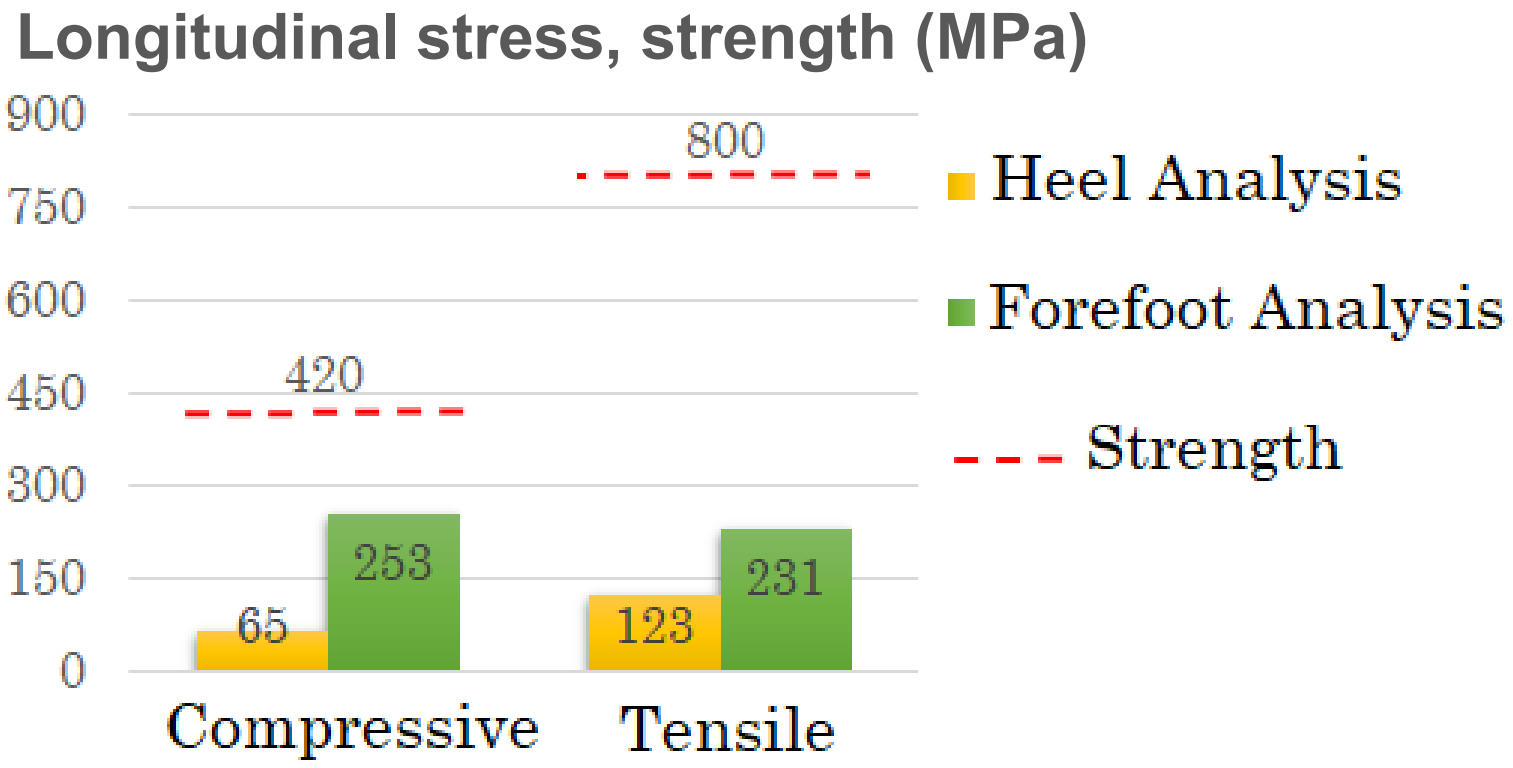


Heel Analysis



Forefoot Analysis

3D STRESS ANALYSIS



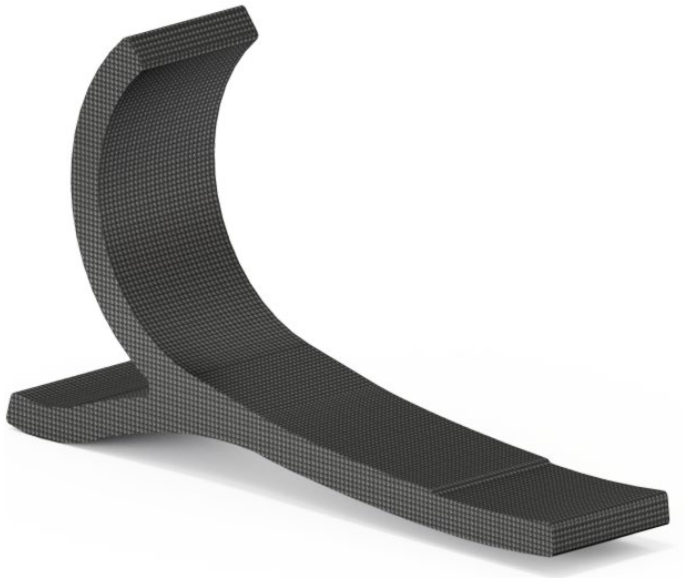
CONCLUSIONS

Development of a numerical optimisation tool

- Development of a versatile Prosthetic Feet optimization tool.
- The tool enables designing the material structure and geometry of the prosthesis.

Material characterization

- Greater insight into the behavior of advanced materials.



3D printed composite foot prostheses seems possible

ACKNOWLEDGEMENTS

- The activities reported are conducted in the framework of the Profil project, funded by INAIL and coordinated by CNR – IPCB

PROFIL

- The activities reported herein

- We acknowledge contributions from all the other partners