



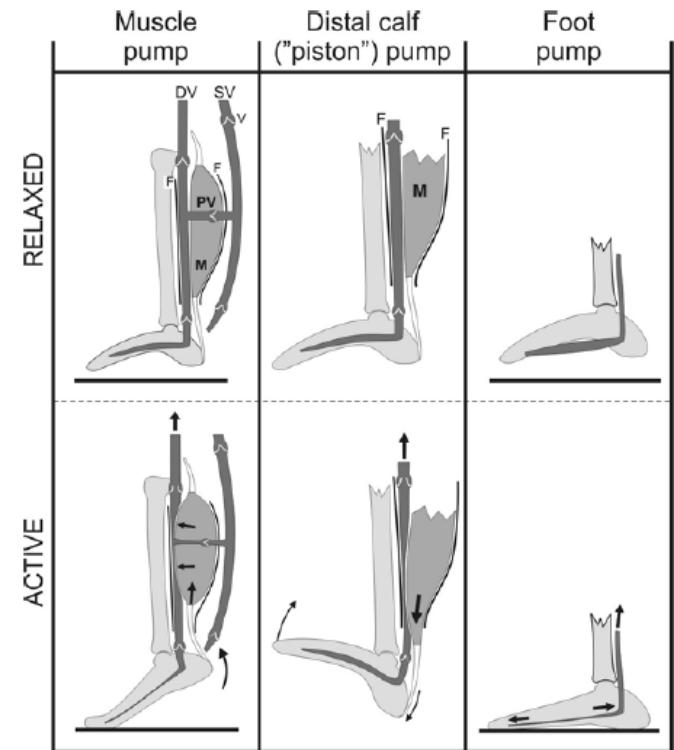
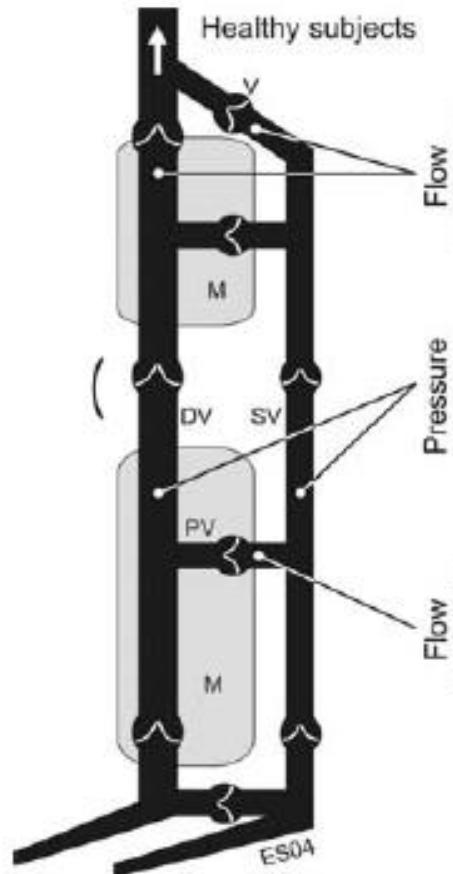
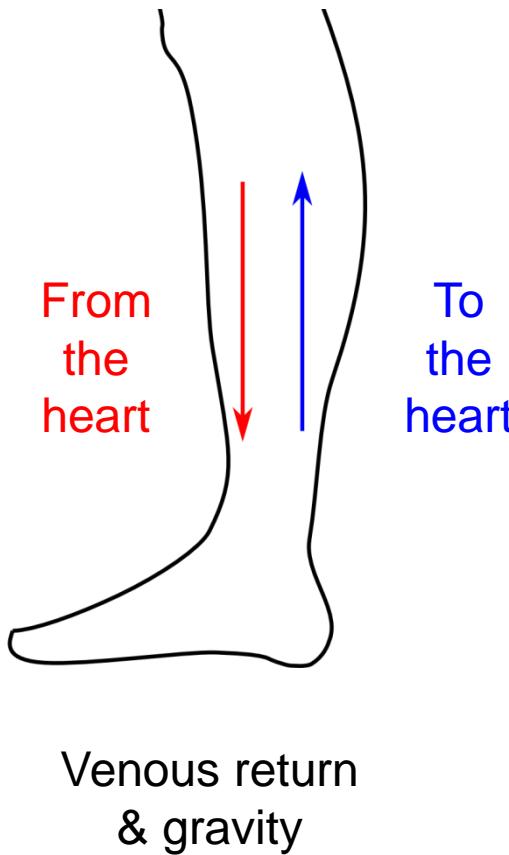
Advanced Treatments and
Technologies in **Wound Care**
15-16 October 2018 | London, UK

***Biomechanical Modelling of
the Human Leg under
Elastic Compression***

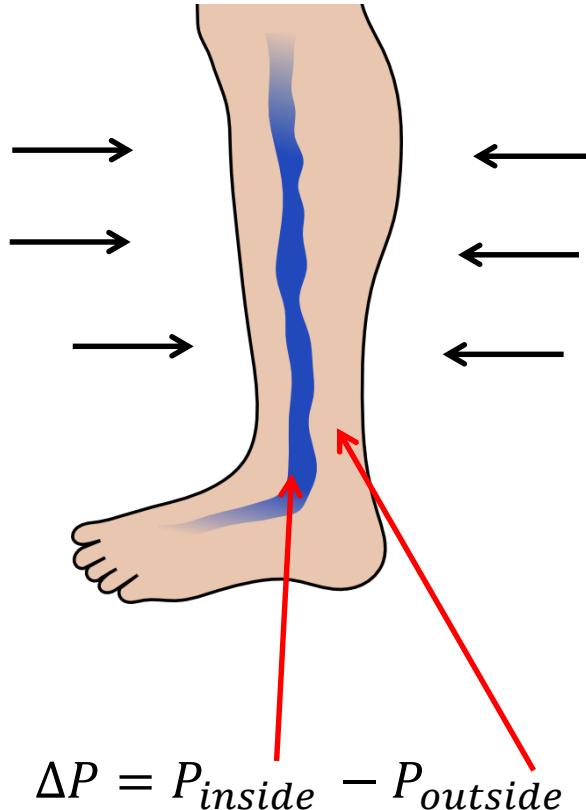
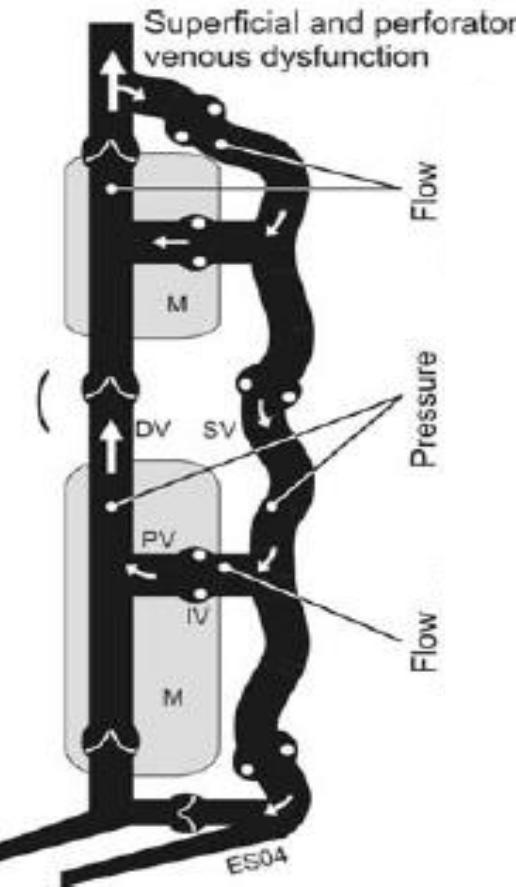


Prof. Stéphane AVRIL

Principles of venous circulation in the leg



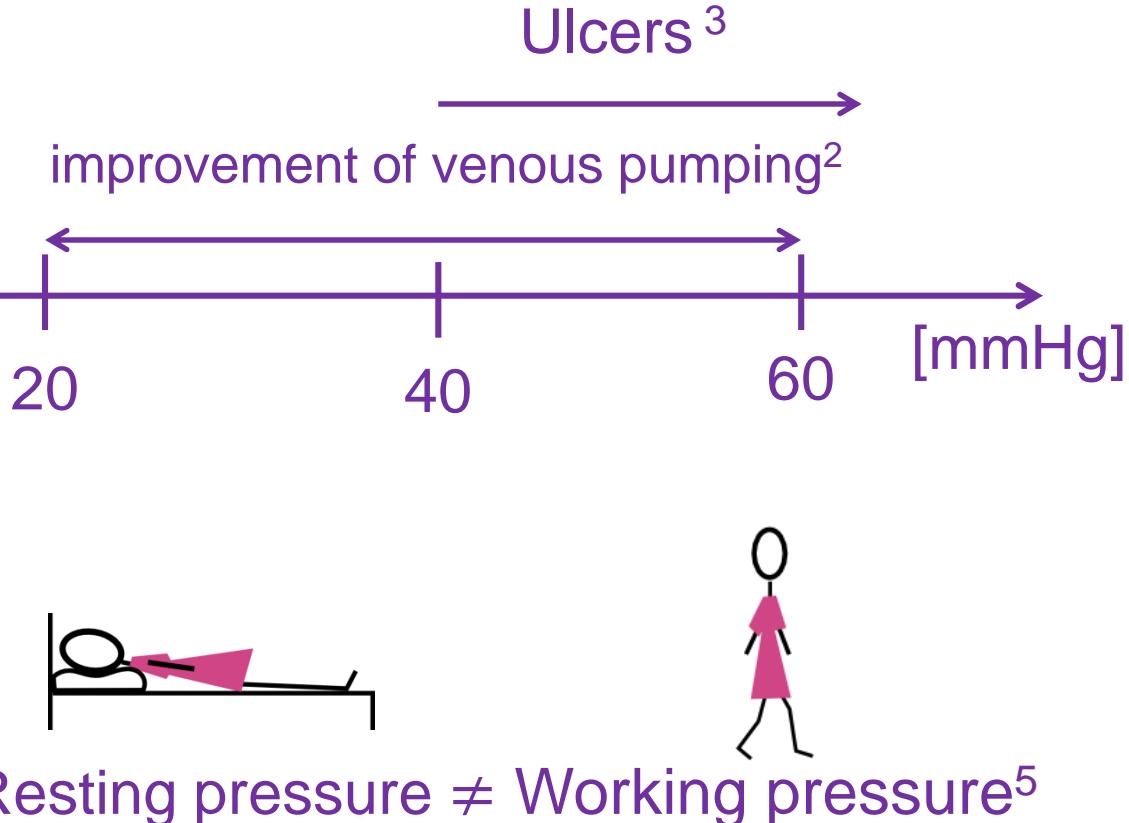
Dysfunction and treatment by elastic compression



$$\nearrow P_{outside} \Rightarrow \downarrow \Delta P$$



Patient and pathology¹



The highest the patient can tolerate ?⁴

Impact of patient specificity on the treatment outcome⁶

¹[Vicaretti, 2010]; ²[Mosti, 2010]; ³[Blair, 1988]; ⁴[HAS, 2010]; ⁵[Dissemond, 2016]; ⁶[Partsch, 2006];

Objectives

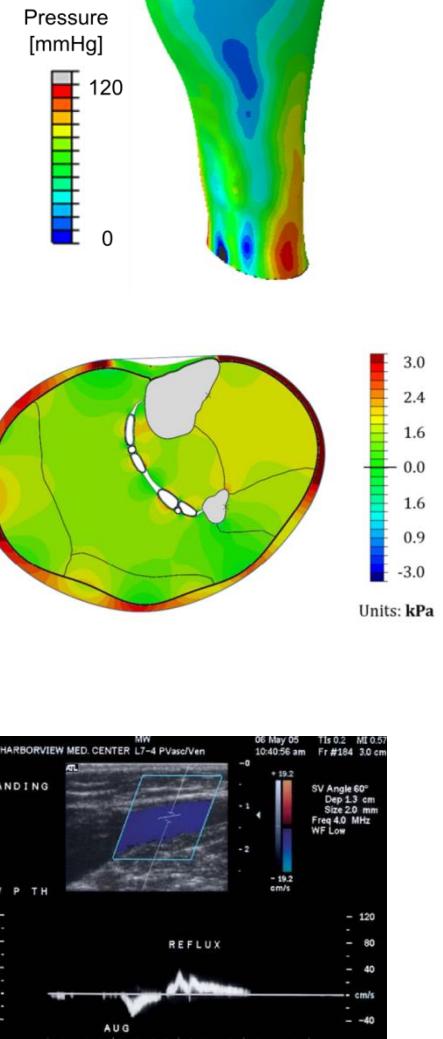
How interface pressure is distributed over the leg ?



How this pressure is transmitted through soft tissues to the vessels ?



How the pressure applied to the veins can enhance venous return ?



Objectives

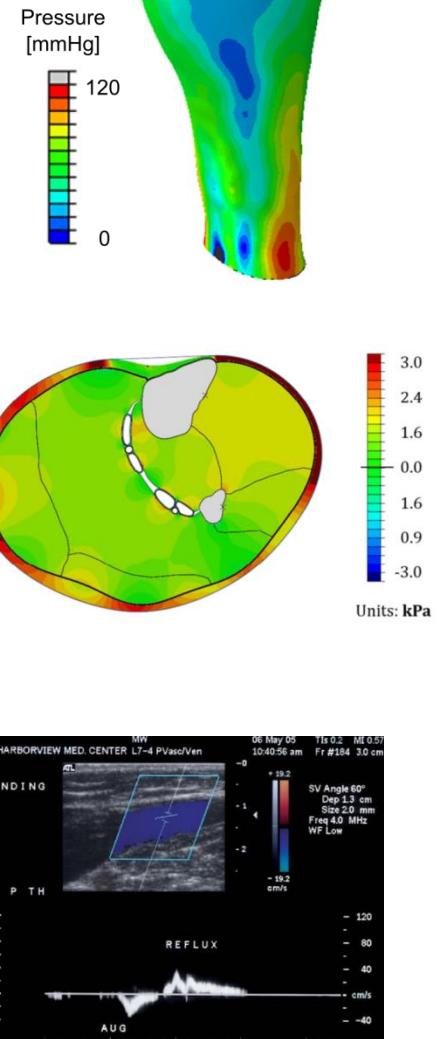
How interface pressure is distributed over the leg ?



How this pressure is transmitted through soft tissues to the vessels ?

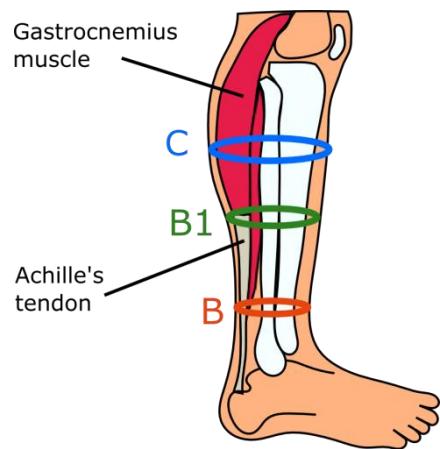


How the pressure applied to the veins can enhance venous return ?



How to assess interface pressure?

In vivo measurements



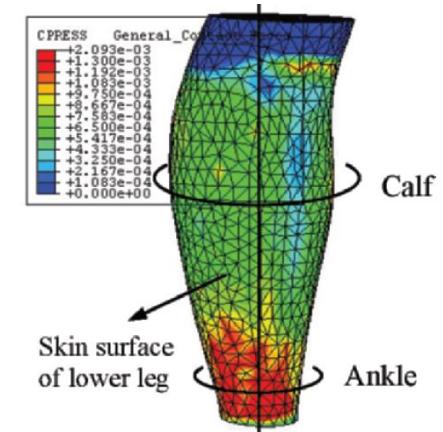
[Prestandard, 2001]

Laplace's Law

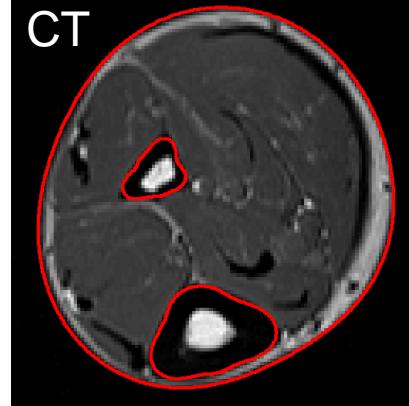
A diagram of a semicircular arch. Two downward-pointing arrows labeled T represent tension applied at the two ends of the chord. A green arrow labeled r_c indicates the radius of curvature of the arch. The formula for interface pressure is given as:

$$P = \frac{T}{r_c}$$

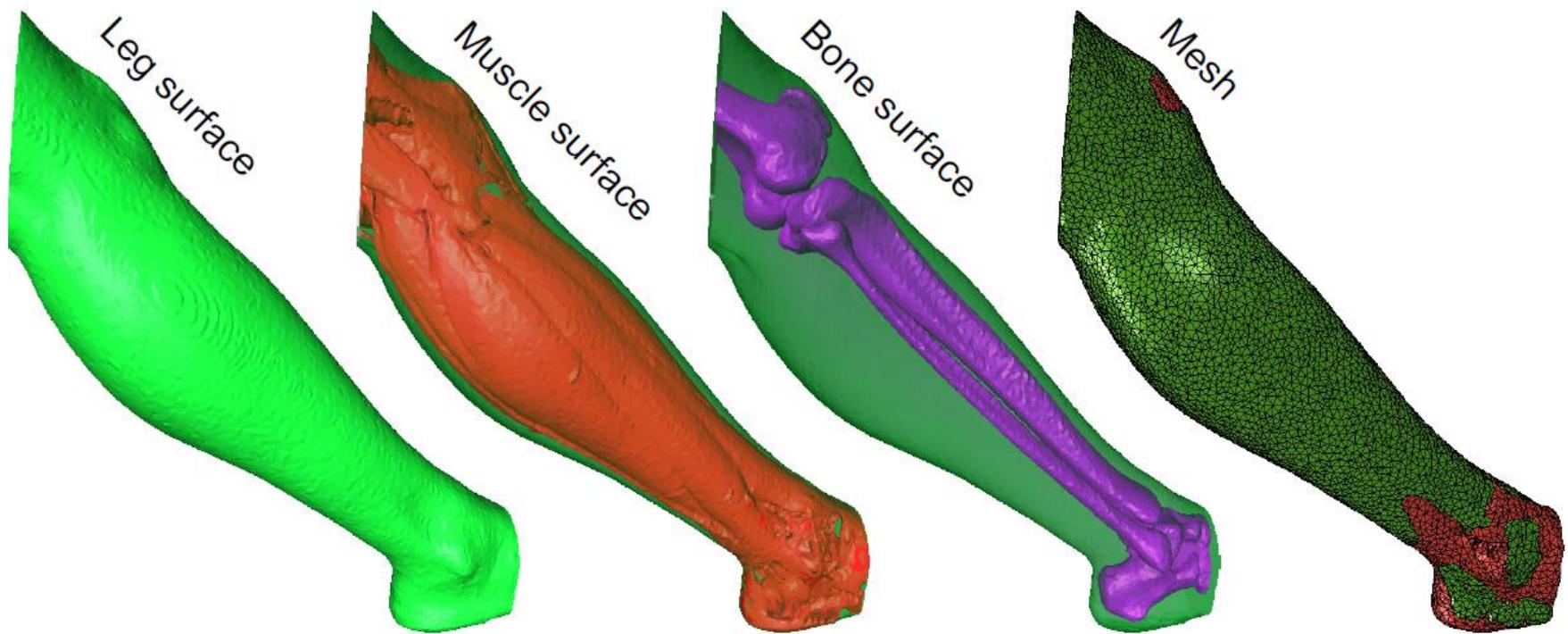
Numerical simulation



[Dai, 2007]



Model reconstruction by image segmentation

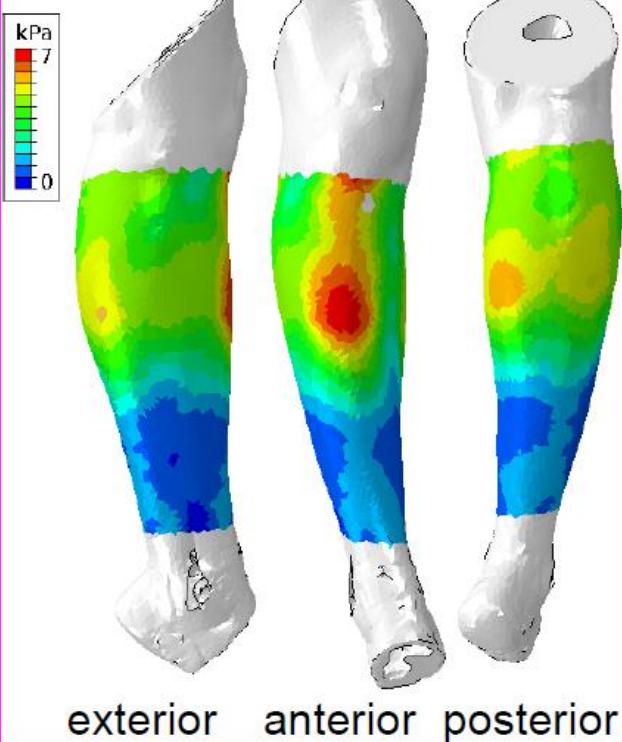


L. Dubuis, S. Avril, J. Debayle and P. Badel, *CMBBE*, vol 15, number 1, pages 3–11, 2012.

The Laplace law

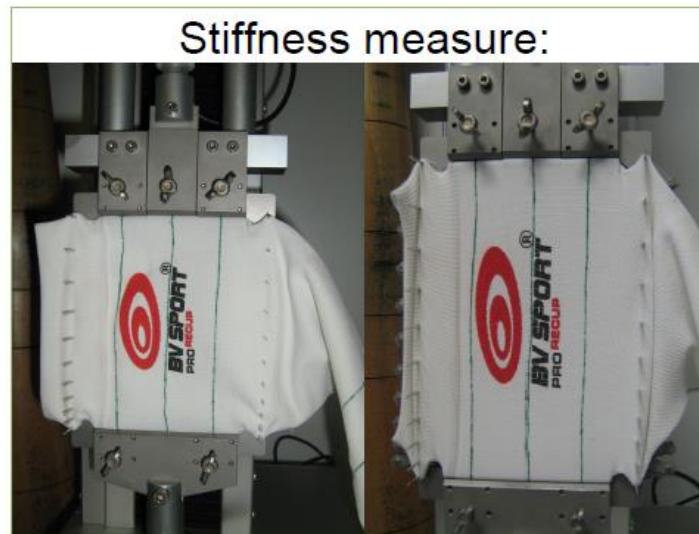
→ Pressure of the sock: the Laplace law

Pressure distribution

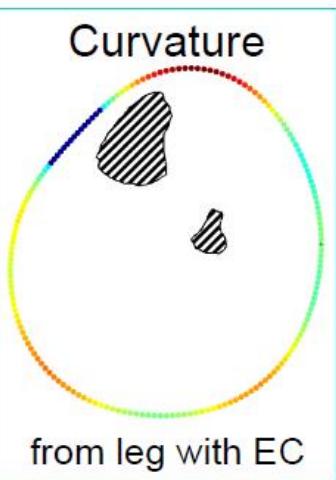


$$P = \text{Stiff} \frac{\varepsilon}{Rc}$$

$$\frac{\text{Leg perimeter} - \text{Sock perimeter}}{\text{Sock perimeter}}$$



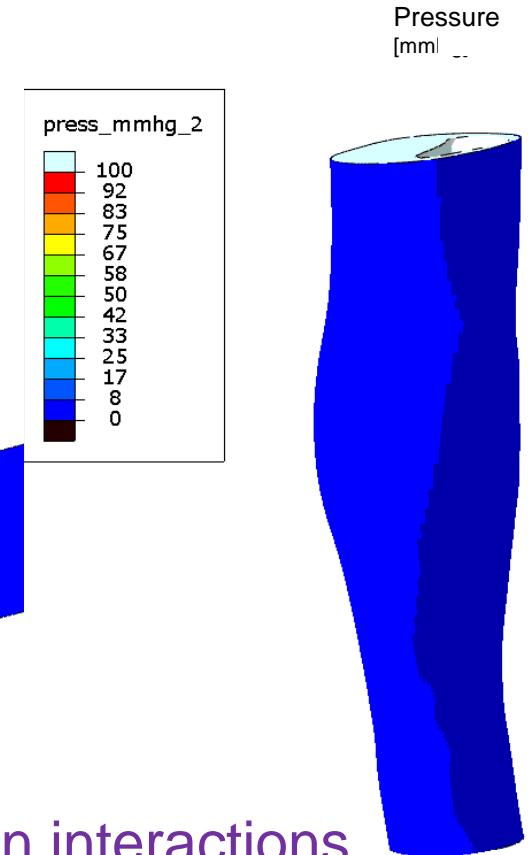
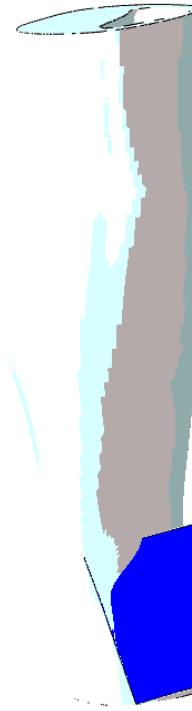
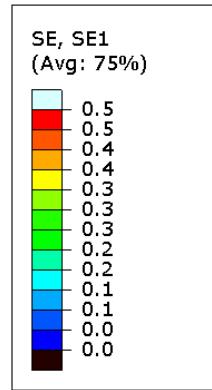
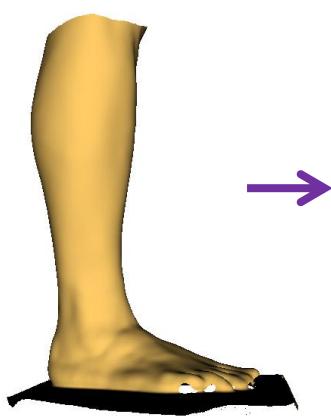
Curvature



from leg with EC

L. Dubuis, S. Avril, J. Debayle and P. Badel, *CMBBE*, vol 15, number 1, pages 3–11, 2012.

Finite Element approach



$$Leg = \sum_{k=1}^K \alpha_k \phi_k$$

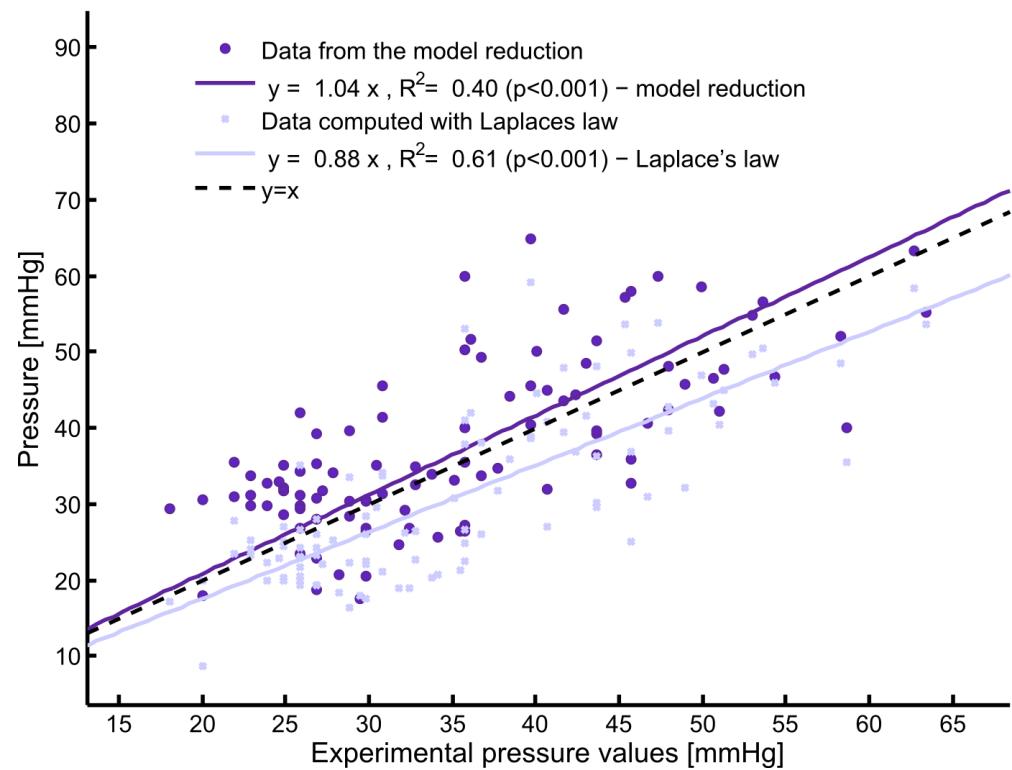
Bandage stretch = 1.3

Skin-to-bandage & Bandage-to-bandage friction interactions

Design of Experiments: 9 simulations with varying parameters

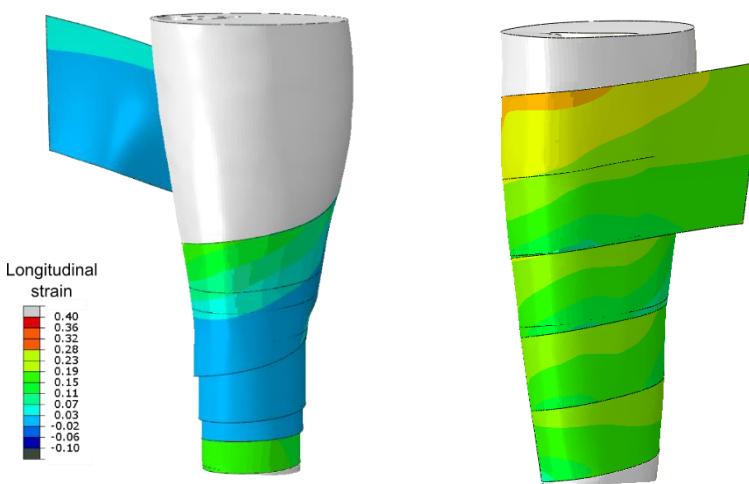
Chassagne, F., Molimard, J., Convert, R., Giroux, P., & Badel, P. Annals of biomedical engineering, 44(10), 3096–3108., 2016,

Validation against experimental measurements



Linear elastic behavior of bandages

Skin-to-bandage friction & leg morphology



Objectives

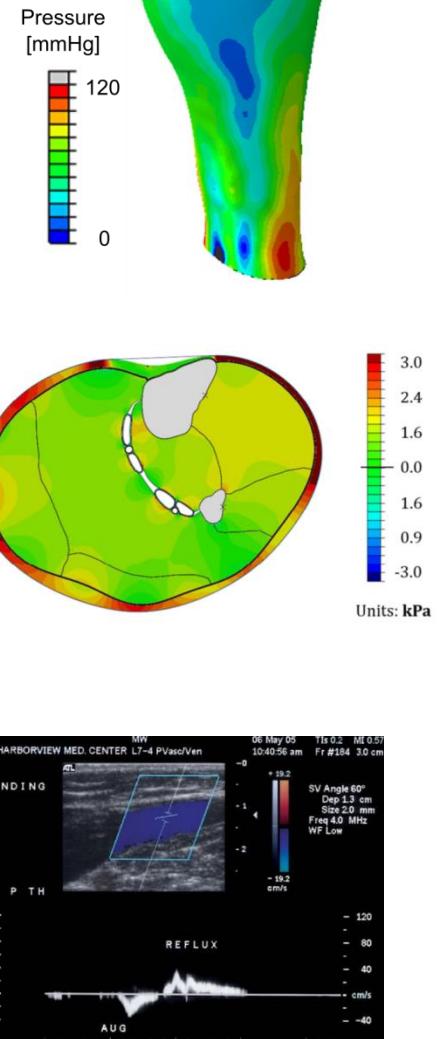
How interface pressure is distributed over the leg ?



How this pressure is transmitted through soft tissues to the vessels ?

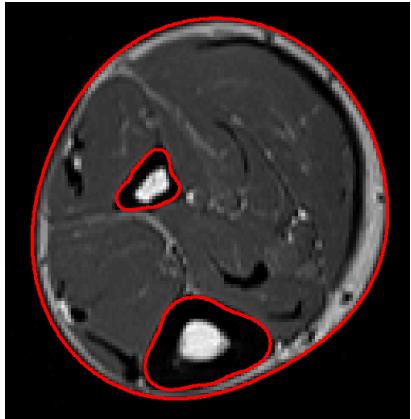


How the pressure applied to the veins can enhance venous return ?

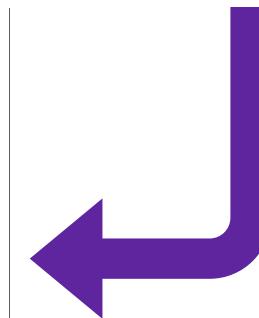
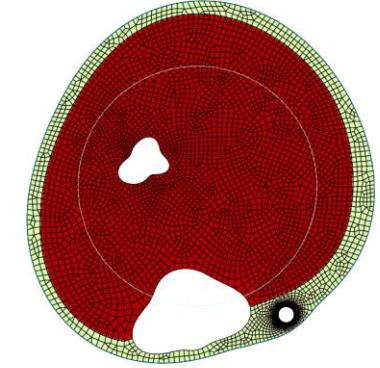
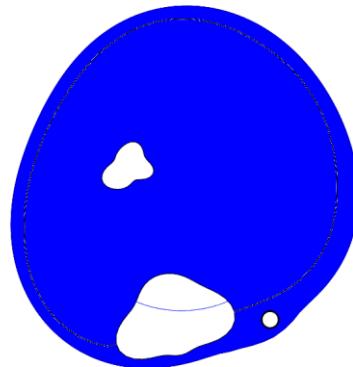
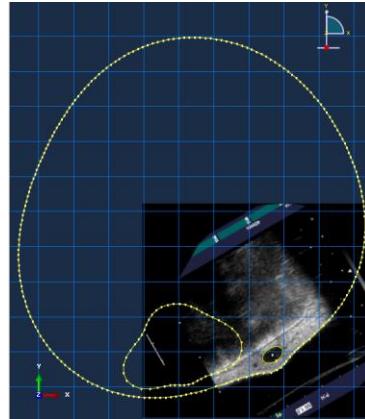


General approach of FE modeling

CT or MRI

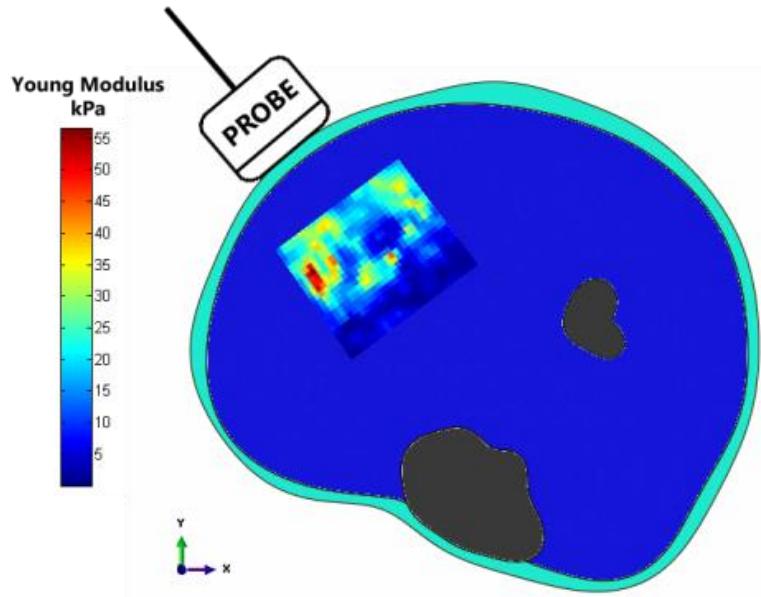


US

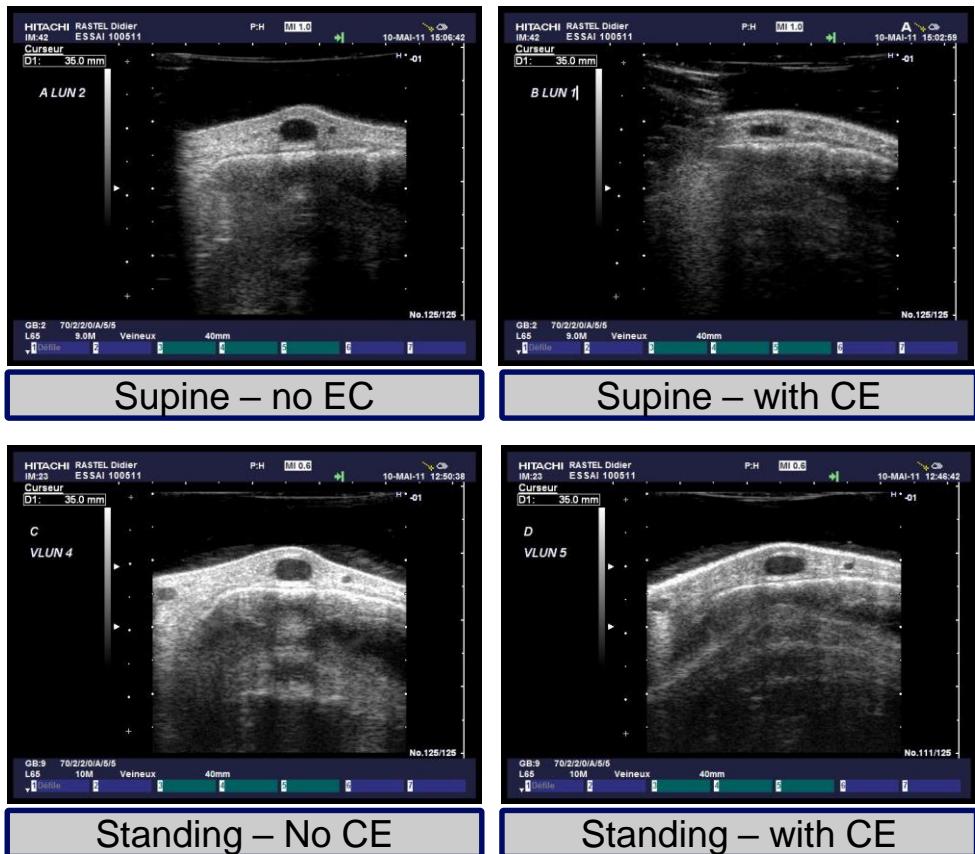


Inputs of the Finite-Element model

US elastography

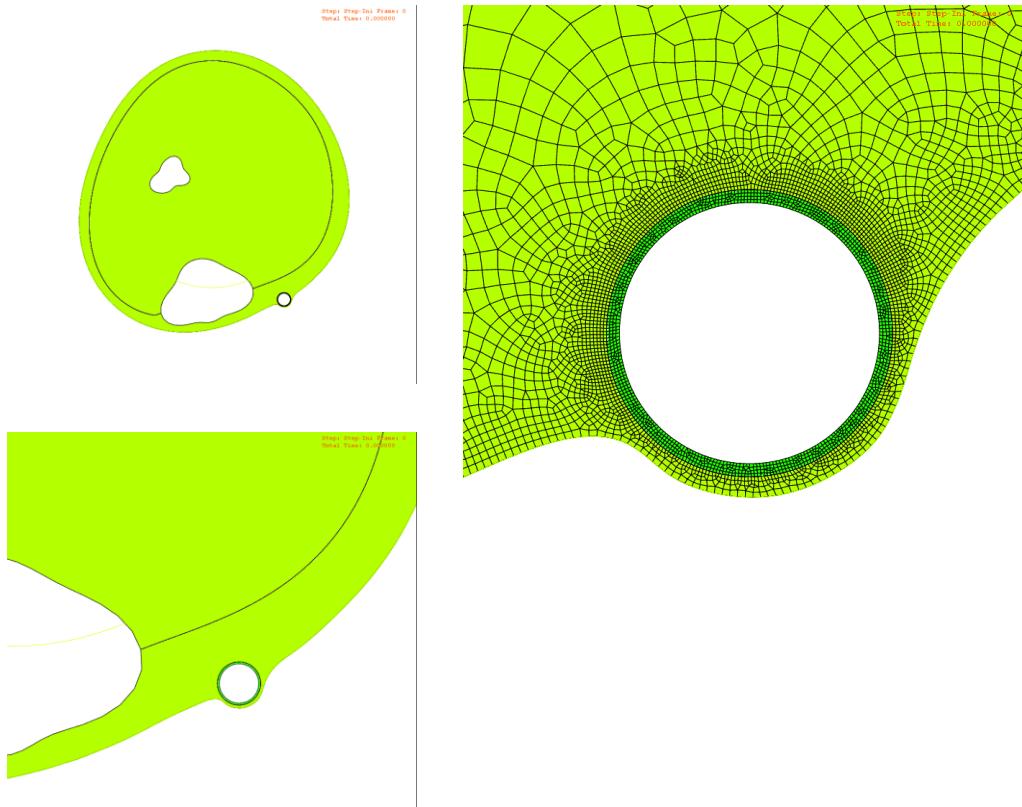


Traditional ultrasound imaging

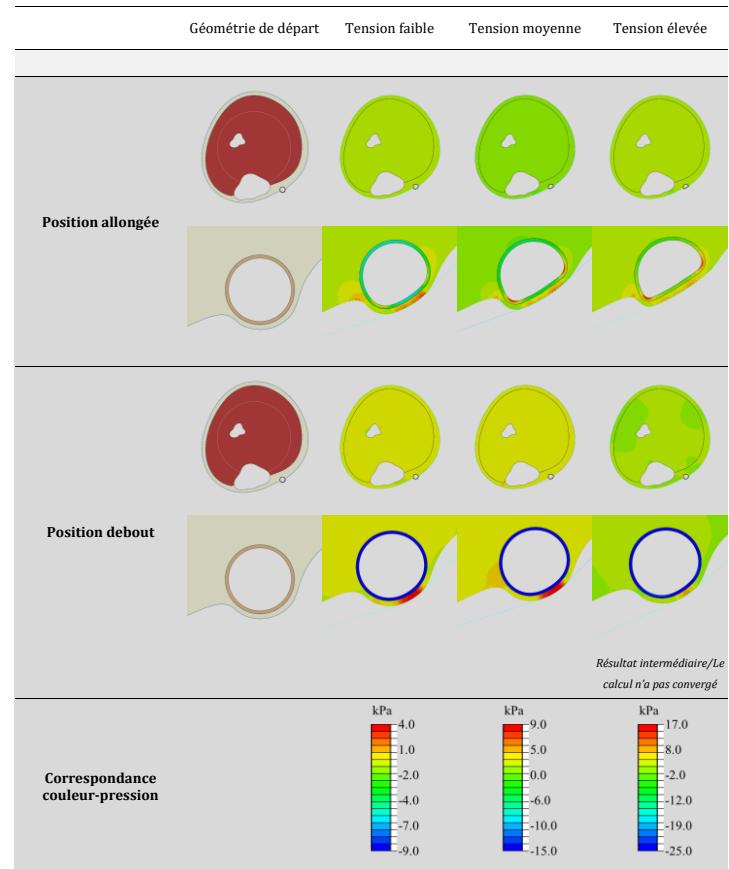


Frauzzi F, Badel P, ... Avril, S. *IEEE Transactions on Biomedical Engineering*, 62(4), 1011–1019, 2015.

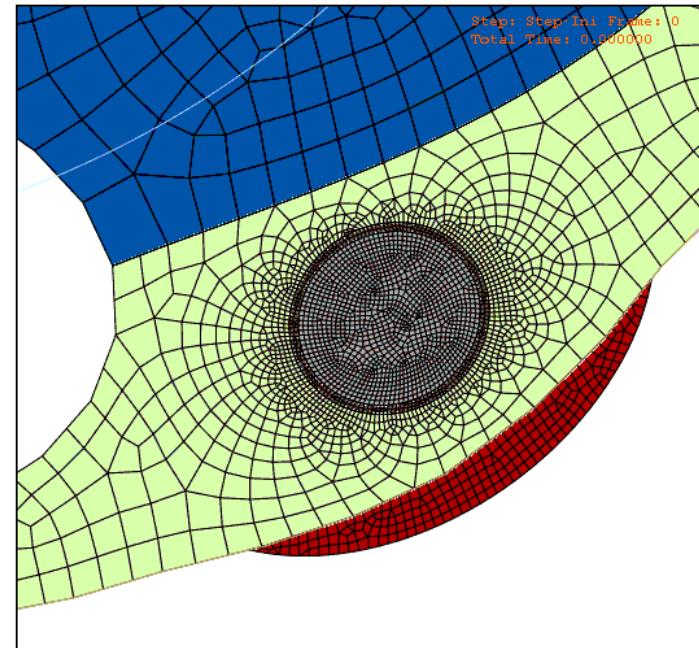
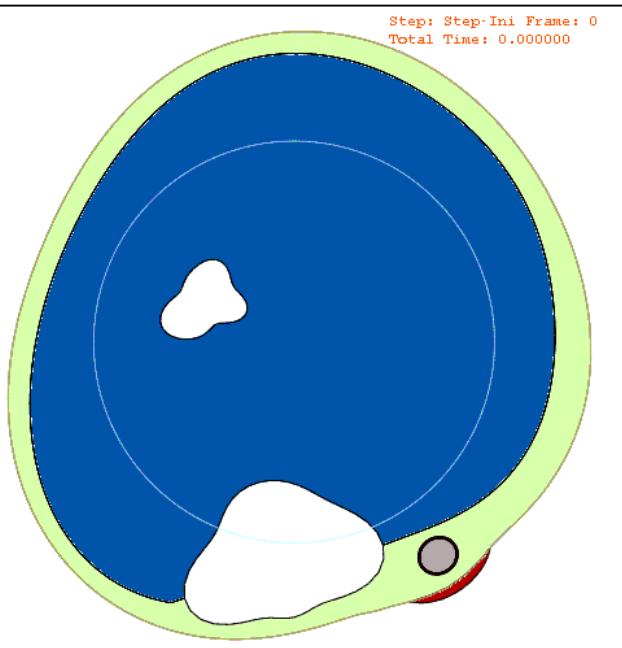
Response of superficial veins



Rohan, C. Y., Badel, P., Lun, B., Rastel, D., & Avril, S. *Journal of biomechanics*, 46(3), 599–603, 2013



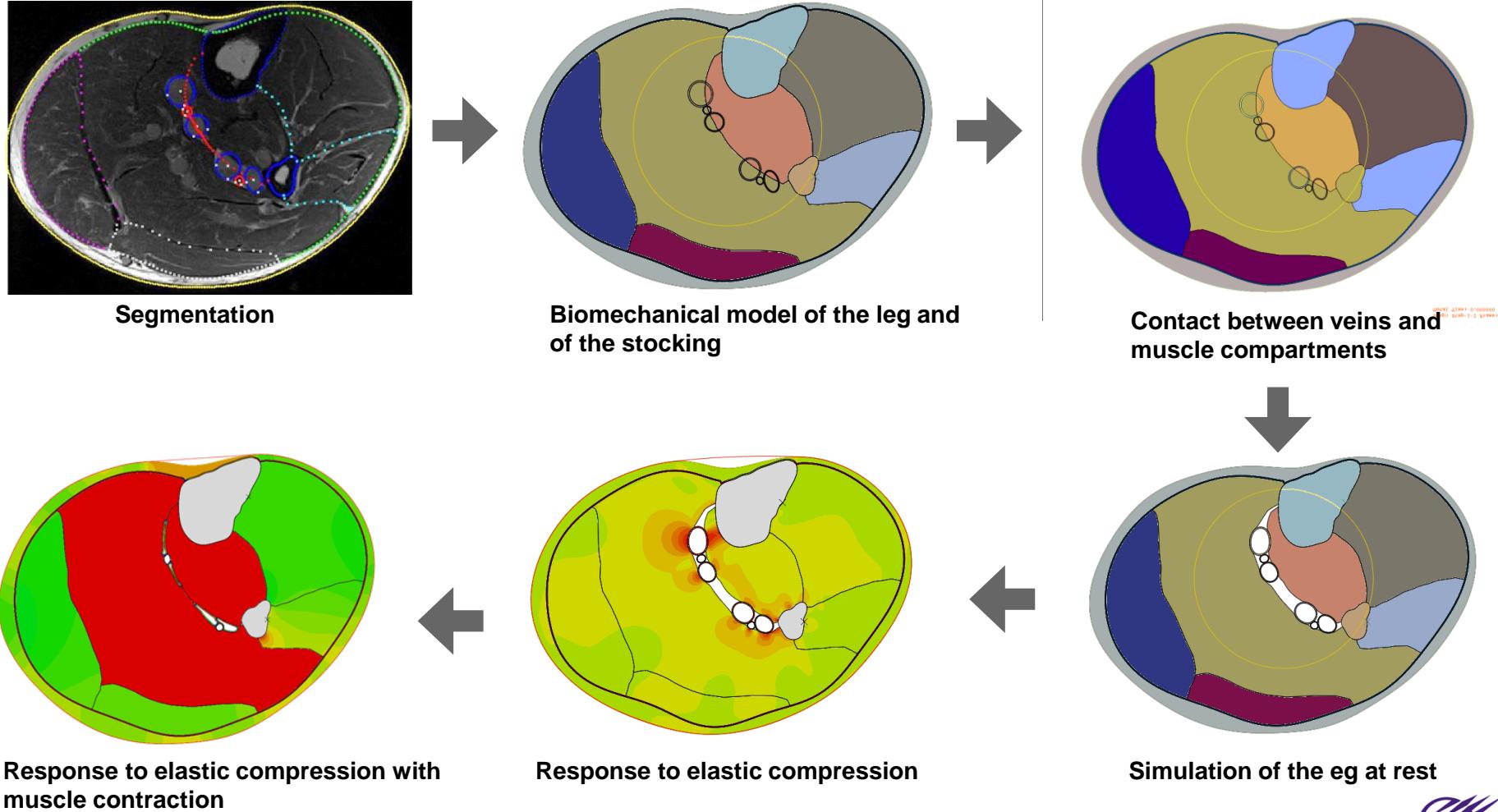
Simulation of the sclerotherapy treatment



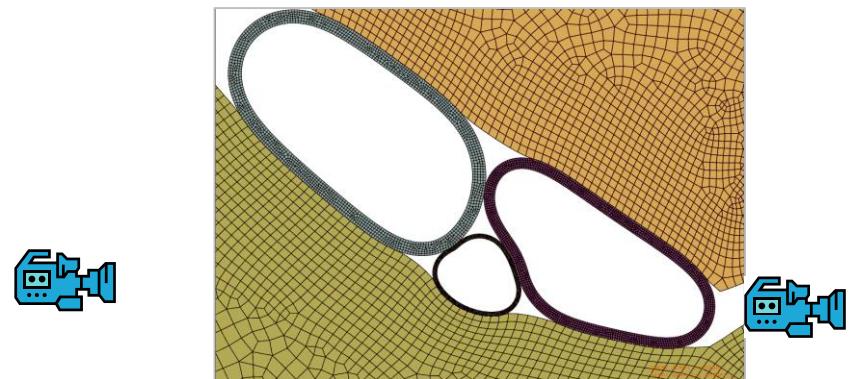
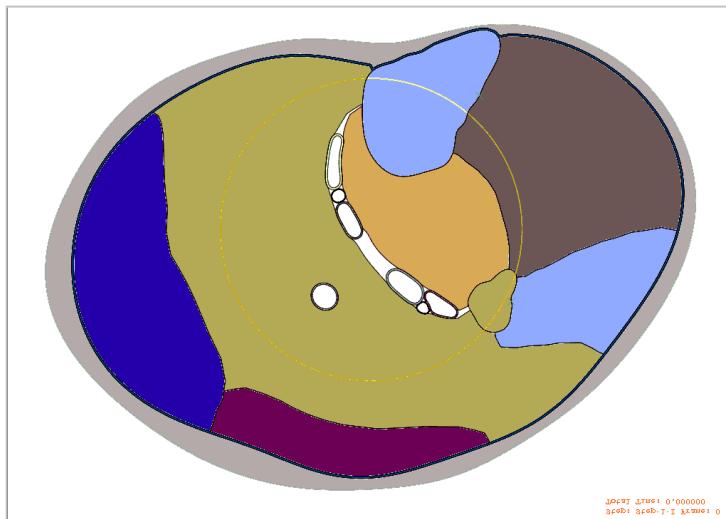
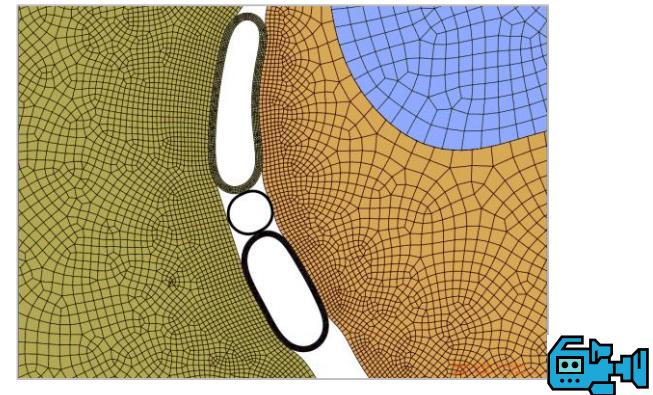
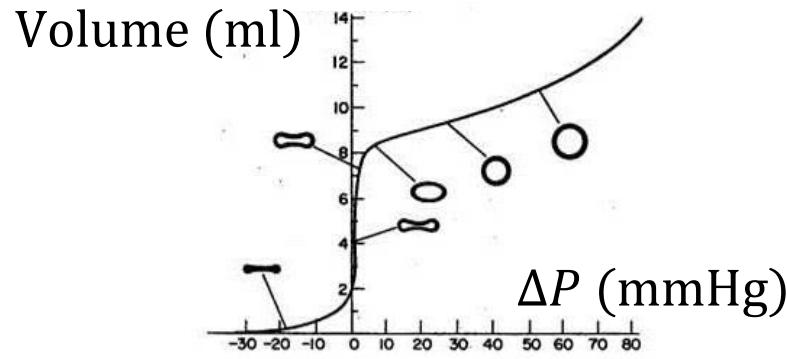
SIGVARIS
LIFE FOR LEGS

Rohan, C. Y., Badel, P., Lun, B., Rastel, D., & Avril, S. *Journal of biomechanics*, 46(3), 599–603, 2013

Simulation strategy for deep veins

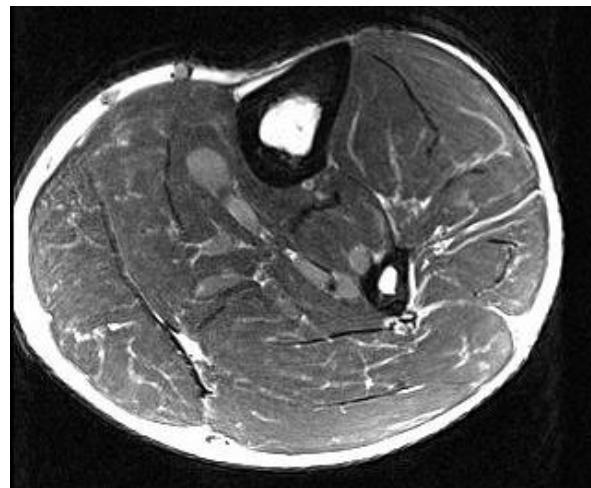
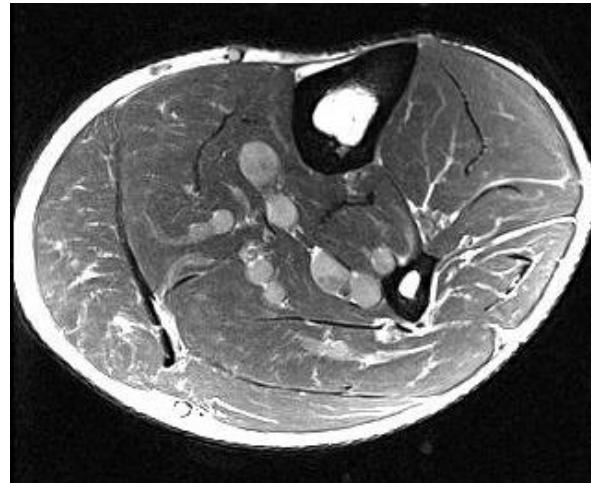
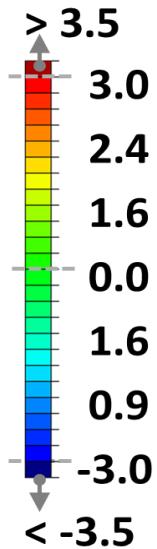
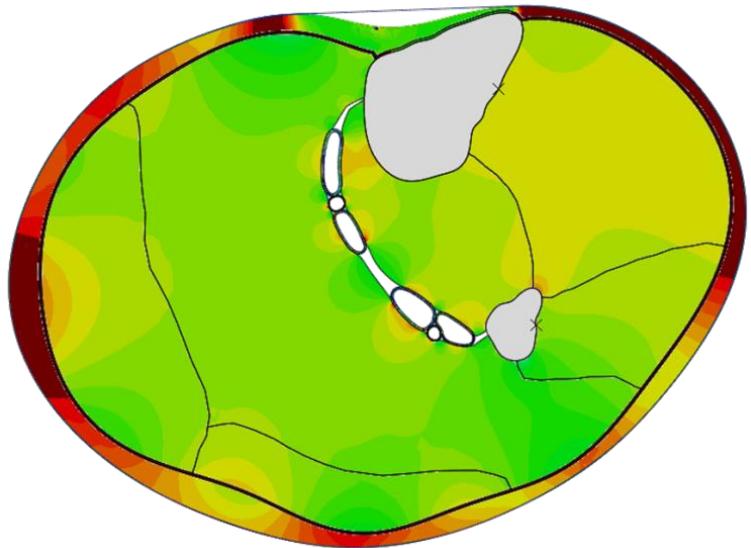


Response of deep veins predicted by FE models



Validation

Pressure distribution (kPa)



No contraction

With contraction

Rohan, P. Y., Badel, P., Lun, B., Rastel, D., & Avril, S. *Annals of biomedical engineering*, 43(2), 314–324, 2015.

Objectives

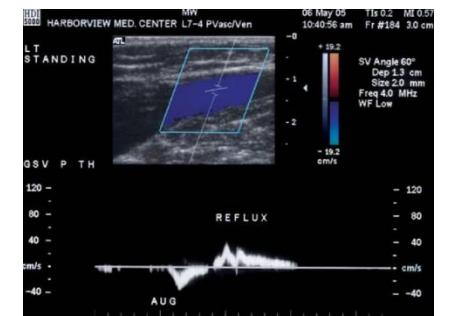
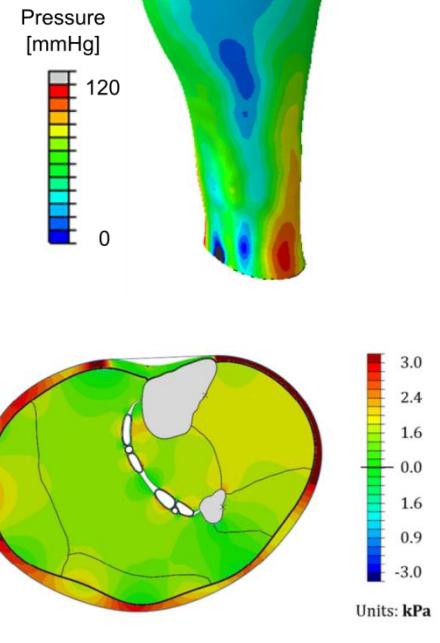
How interface pressure is distributed over the leg ?



How this pressure is transmitted through soft tissues to the vessels ?

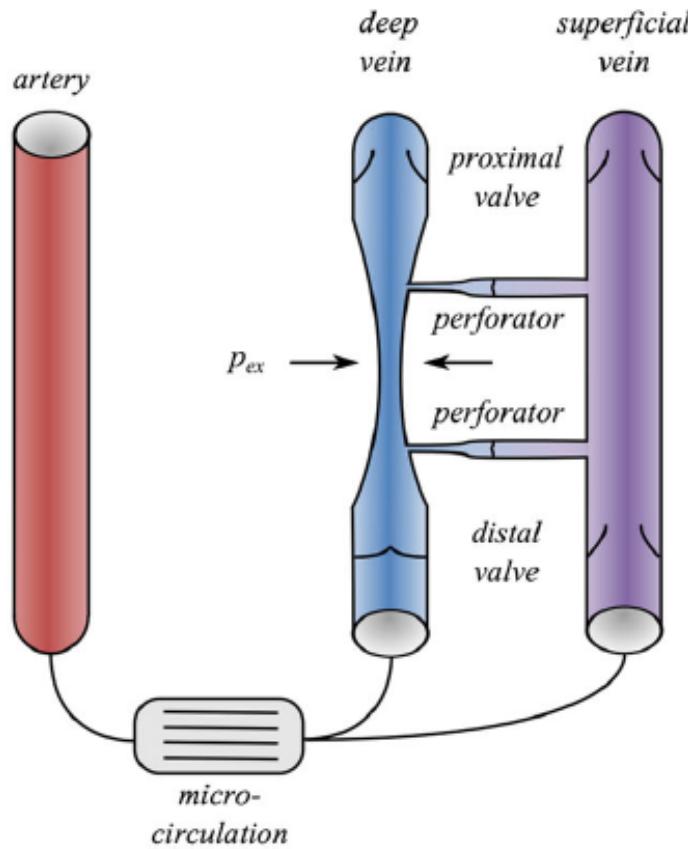


How the pressure applied to the veins can enhance venous return ?

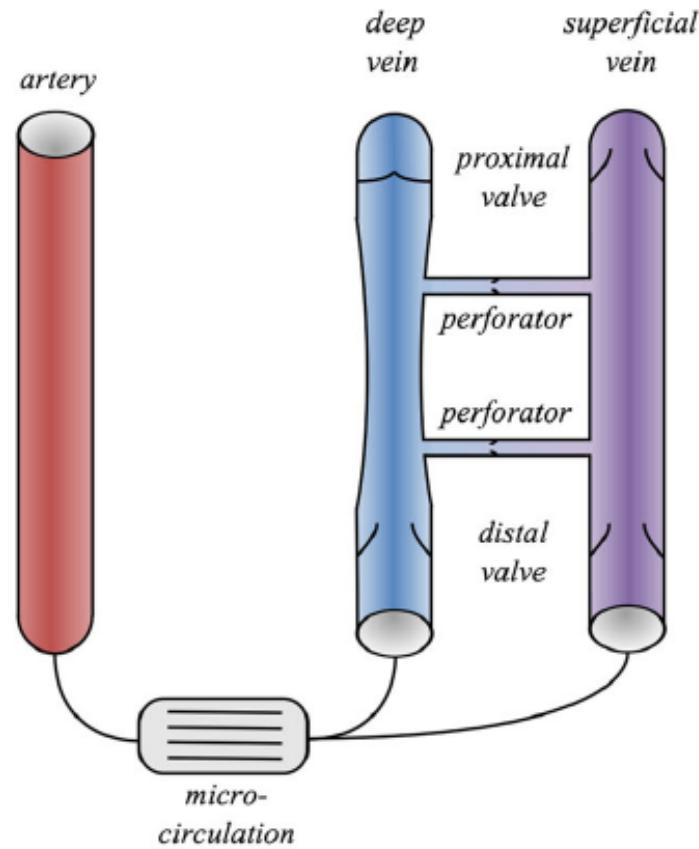


Simplified model of the calf hemodynamics

A CONTRACTION

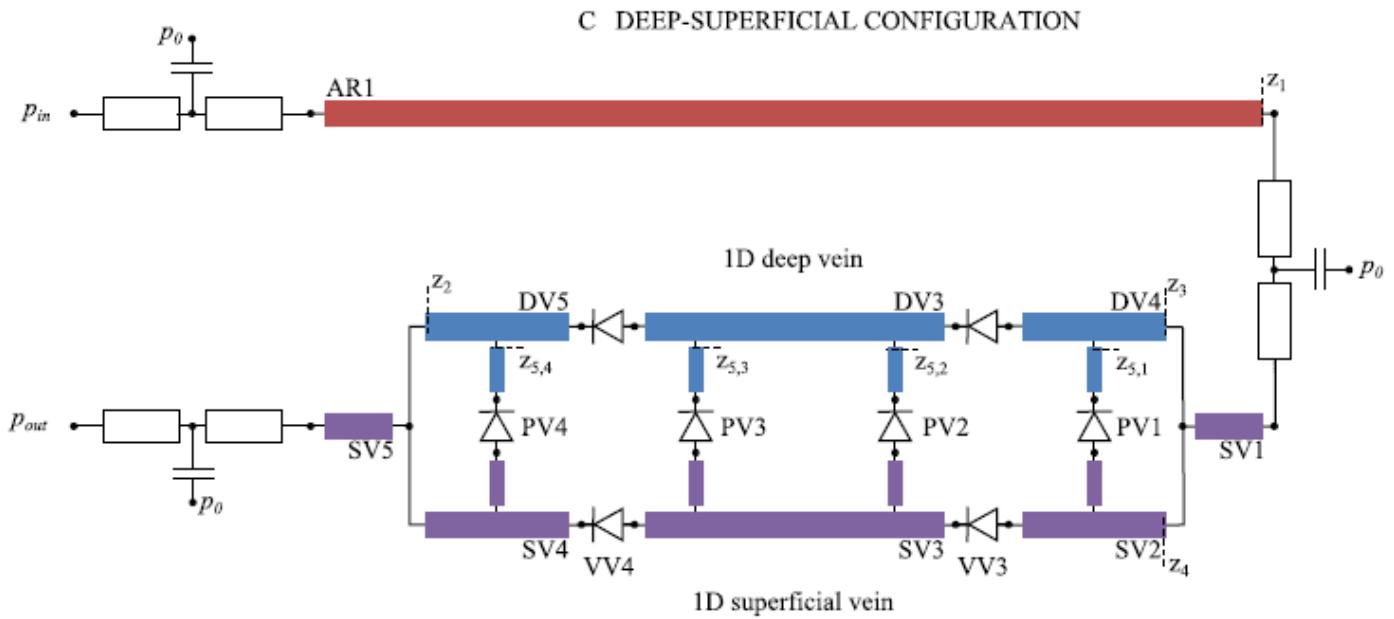


B RELAXATION



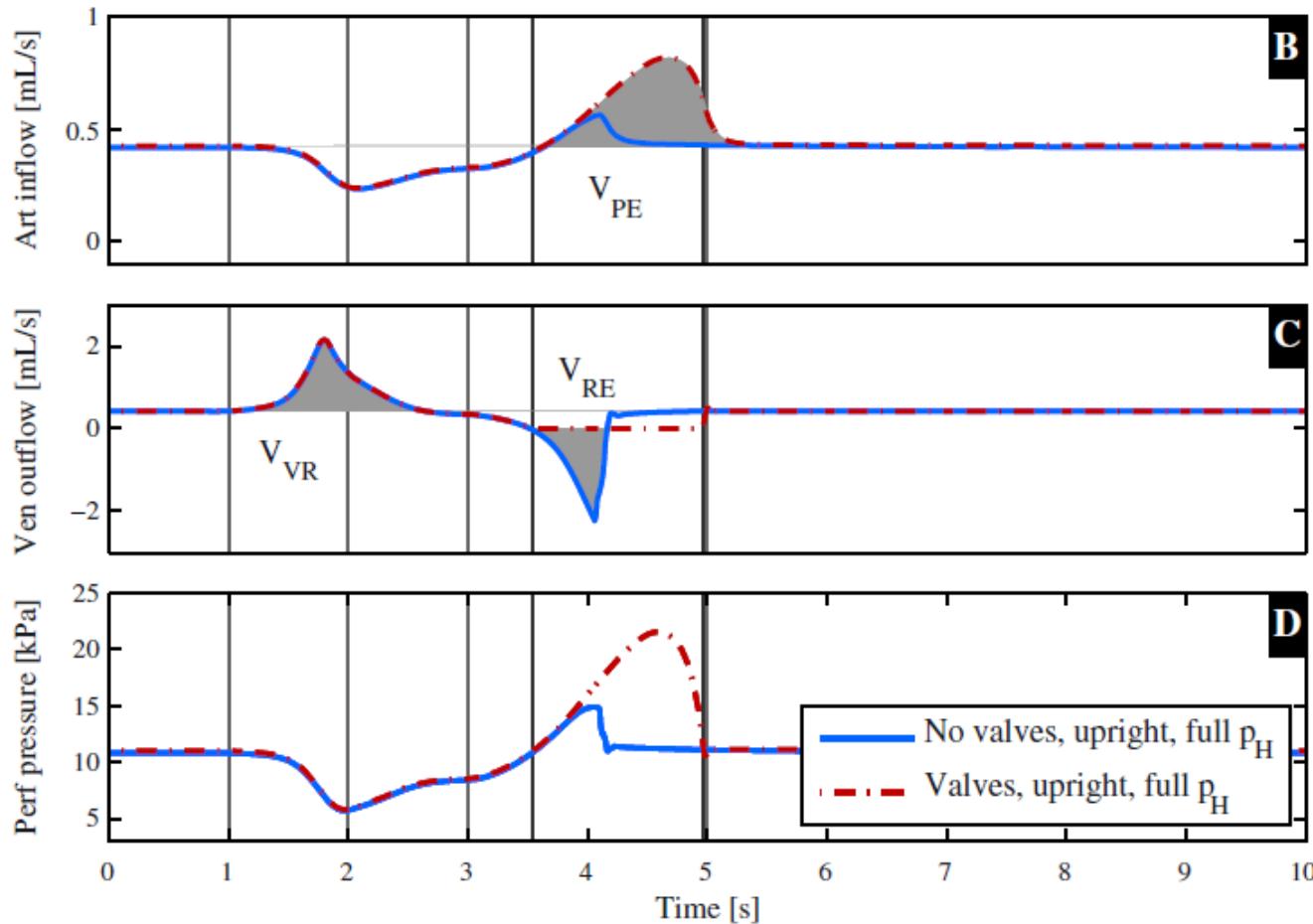
Keijzers et al. *International journal for numerical methods in biomedical engineering*, 31(7), e02714, 2015.

1D finite volume model of the calf hemodynamics including venous return



Keijzers et al. *International journal for numerical methods in biomedical engineering*, 31(7), e02714, 2015.

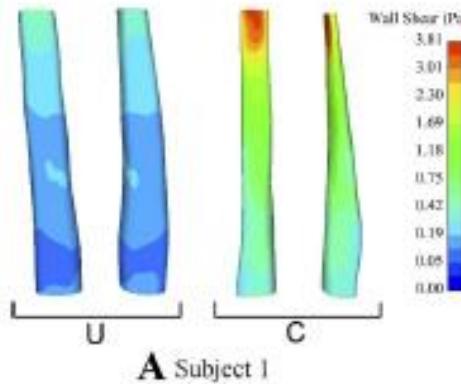
Prediction of alterations in the venous return



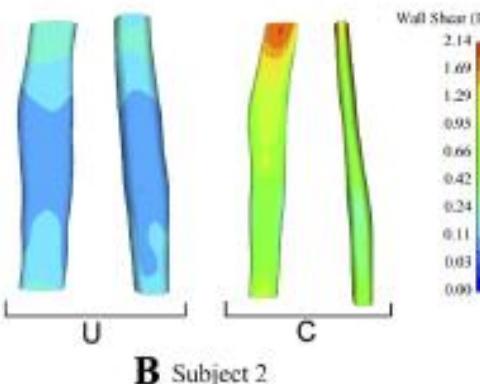
Keijzers et al. *International journal for numerical methods in biomedical engineering*, 31(7), e02714, 2015.

Prediction of risk of thrombosis

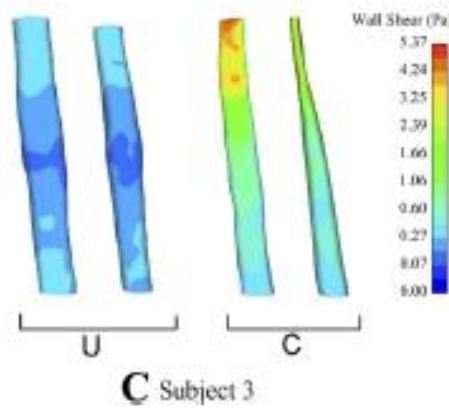
CALF COMPRESSION AND VENOUS SHEAR STRESS



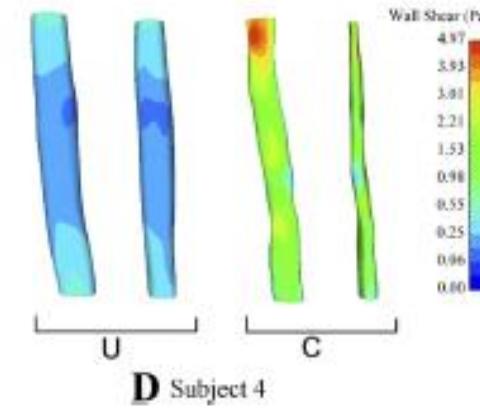
A Subject 1



B Subject 2



C Subject 3

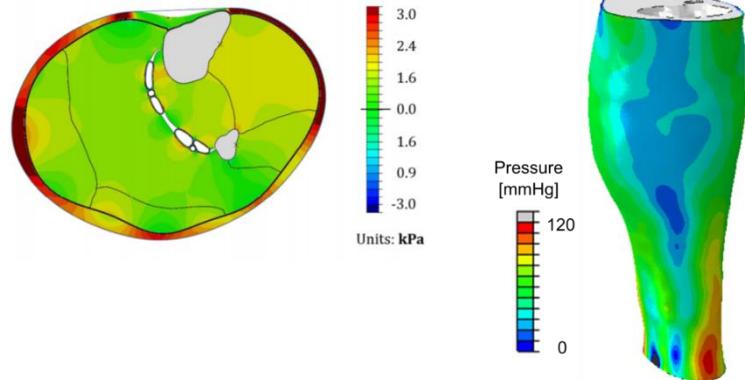


D Subject 4

Downie et al. *American Journal of Physiology–Heart and Circulatory Physiology*, 294(5), H2112–H2120, 2008



Summary



- Digital twin of the human leg under elastic compression.
- Pressure and deformations correctly predicted.
- Circulatory and biological effects are still challenging.

Acknowledgements

- Pierre-Yves Rohan
- Laura Dubuis
- Jean-François Pouget
- Serge Couzan
- Pierre Badel
- Bertrand Lun
- Fanny Frauziols
- Jérôme Molimard
- Fanette Chassagne
- Reynald Convert
- Pascal Giraux

Funding:
ERC-2014-CoG BIOLOCHANICS



European Research Council
Established by the European Commission
©ERC

