

Numerical determination of an unloaded configuration for anatomical structure

Détermination numérique d'une configuration libre de contraintes de structures anatomiques

Nathan COLLIN^{1,2}
Bertrand WATTRISSE¹, Simon LE FLOC'H¹
Dominique AMBARD², Julien SIGUENZA²

¹ LMGC, Montpellier
² Sim&Cure, Montpellier
nathan.collin@umontpellier.fr
n.collin@sim-and-cure.com

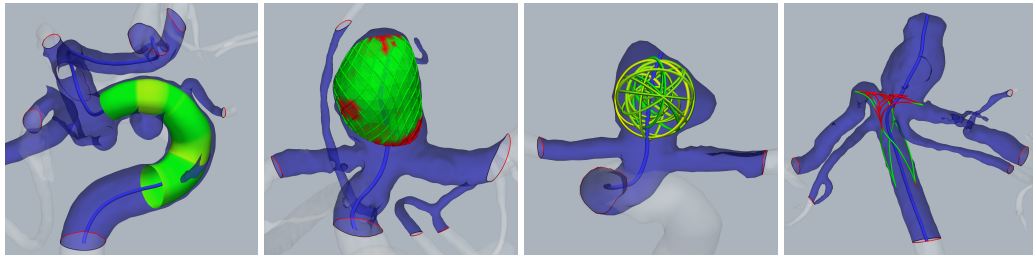
GdR Mécabio, Décembre 2022



Patient specific computation of intra vascular devices deployment

Sim&Cure

SECURE YOUR TREATMENT





Summary

State of the art of unloaded configuration research

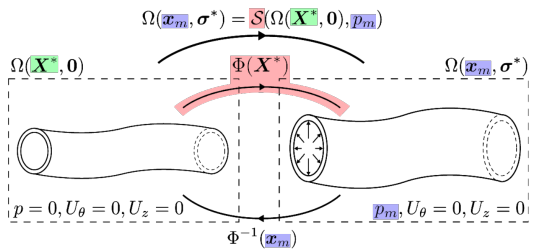
Adaptation of the algorithm to the particular case of shell modelization

Applications of the unloaded state resarch's algorithm on simple cases.

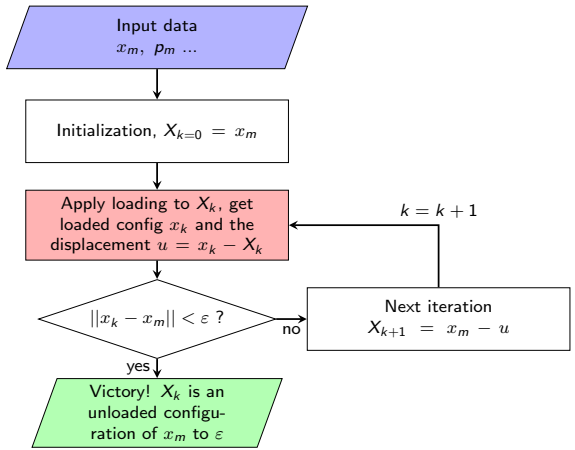
Applications of the unloaded state resarch's algorithm on patient specific aneurysms geometry

Conclusions, limitations and outlooks

State of the art of unloaded configuration research

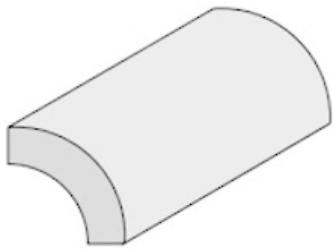


Inverse problem illustration, from *A computational method to assess the in vivo stresses and unloaded configuration of patient-specific blood vessels*, J. Bols et al. (2013)

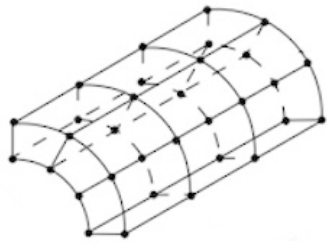


Fixed Point strategy for unloaded configuration research

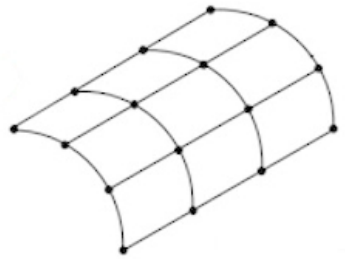
Particular case of shell modelization



- ▶ Solid
- ▶ continuous media



- ▶ Volumic modelization
- ▶ The solid must be discretized in its thickness
- ▶ 3 dofs per nodes (3 displacements)

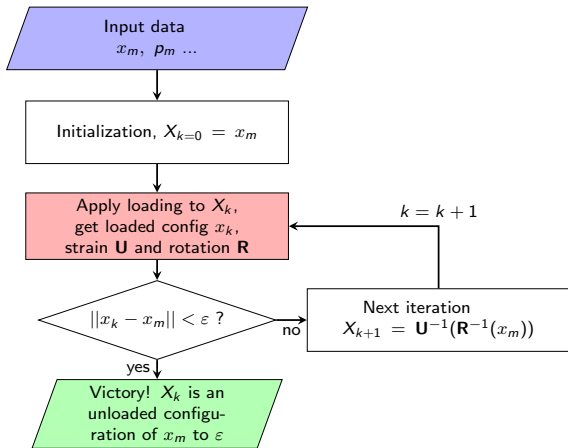


- ▶ Shell modelization
- ▶ Only the median surface of the solid is discretized
- ▶ 6 dofs per nodes (3 displacements + 3 rotations)

Fixed Point algorithm modification

$u = x_k - X_k$ describe the displacement of the solid for a volumic modelization but is not enough in the case of shell modelization and more complex geometry than found in the litterature.

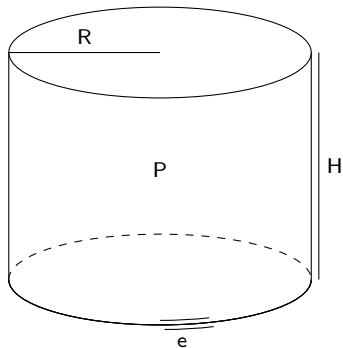
In our case, the subtraction of the rotation must be taken into account.



Update of the unloaded configuration research's algorithm

Application - Circular artery

Direct problem

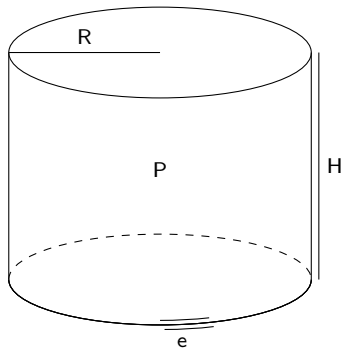


Cylinder of radius R , height H and wall thickness e , with a pressure P within

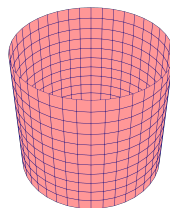
- ▶ Quasi-incompressible hyperelastic material - Neo Hookean potential ($C_{NH} = 2kPa$)
- ▶ Homogeneous pressure ($P = 0.5kPa$)
- ▶ No axial displacement

Application - Circular artery

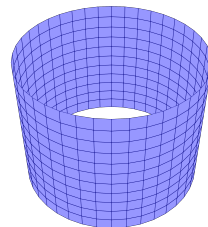
Direct problem



Cylinder of radius R , height H and wall thickness e , with a pressure P within



Initial state, " X^* "
eccentricity $e = 0$

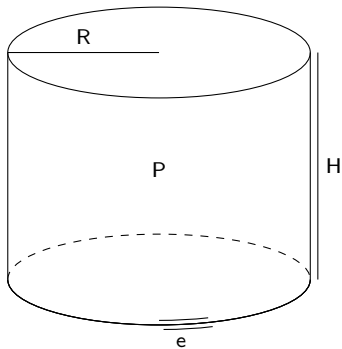


Deformed state, " $x_m = \Phi(X^*)$ "
eccentricity $e = 0$

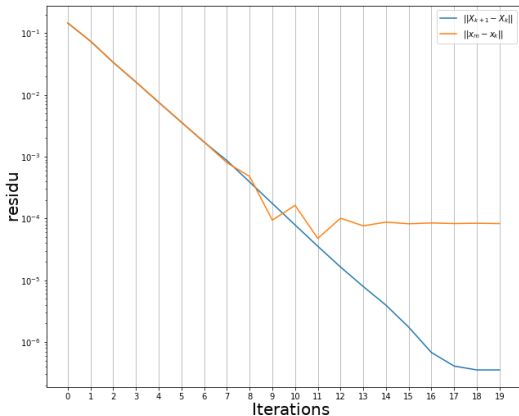
Direct problem of the inflation of a circular artery

Application - Circular artery

Inverse problem



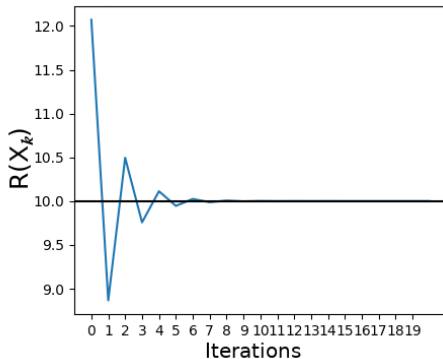
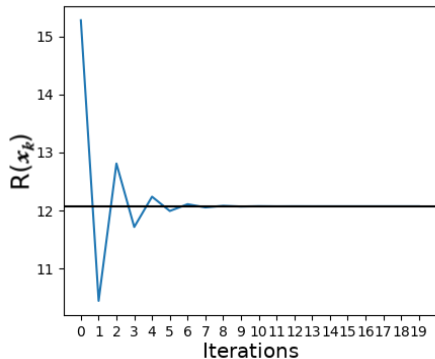
Cylinder of radius R , height H and wall thickness e , with a pressure P within



Algorithm convergence

Application - Circular artery

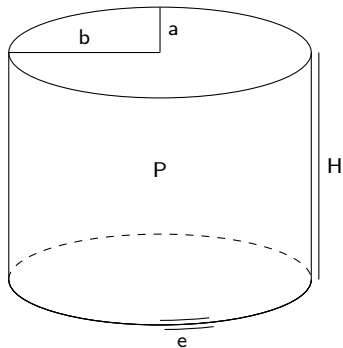
Inverse problem



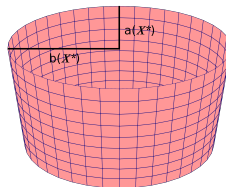
Radius in the deformed and initial state

Application - Elliptical artery I

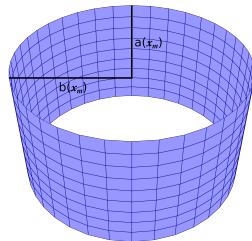
Direct problem



Elliptical cylinder of radius R , height H and wall thickness e , with a pressure P within



Initial state, " X^* "
eccentricity $e \simeq 0.745$

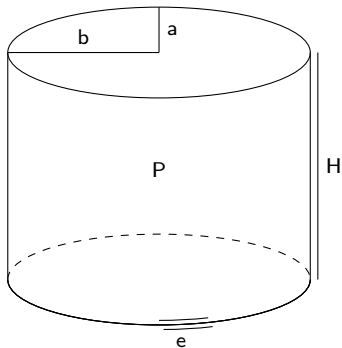


Deformed state, " $x_m = \Phi(X^*)$ "
eccentricity $e \simeq 0.130$

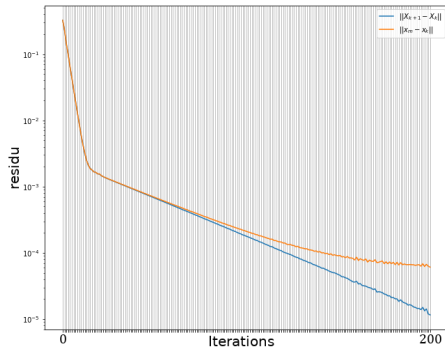
Direct problem of the inflation of an elliptic artery

Application - Elliptical artery I

Inverse problem



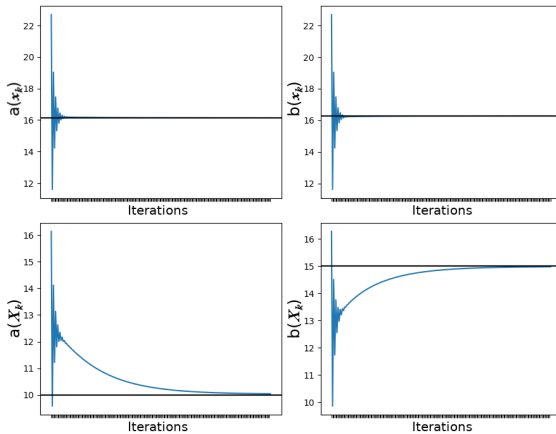
Elliptical cylinder of radius R , height H and wall thickness e , with a pressure P within



Algorithm convergence

Application - Elliptical artery II

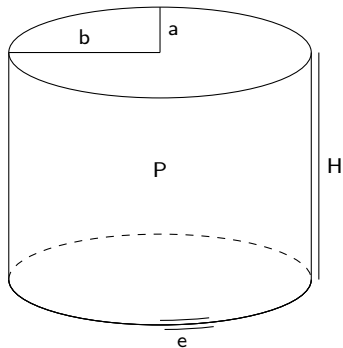
Inverse problem



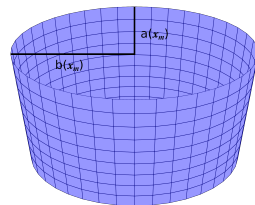
Ellipse parameters in the deformed state

Application - Elliptical artery II

No direct problem for this case



Elliptical cylinder of radius R , height H and wall thickness e , with a pressure P within



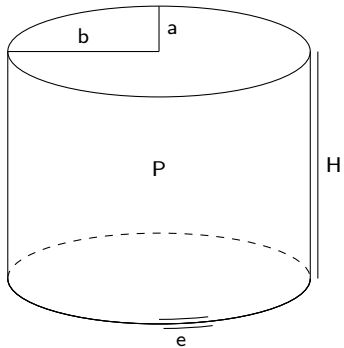
Unknown initial state, " X^* "

Deformed state, " x_m "
eccentricity $e \simeq 0.745$

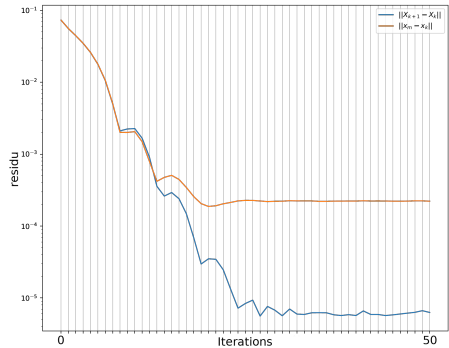
Direct problem of the inflation of an artery, elliptic after inflation.

Application - Elliptical artery II

Inverse problem



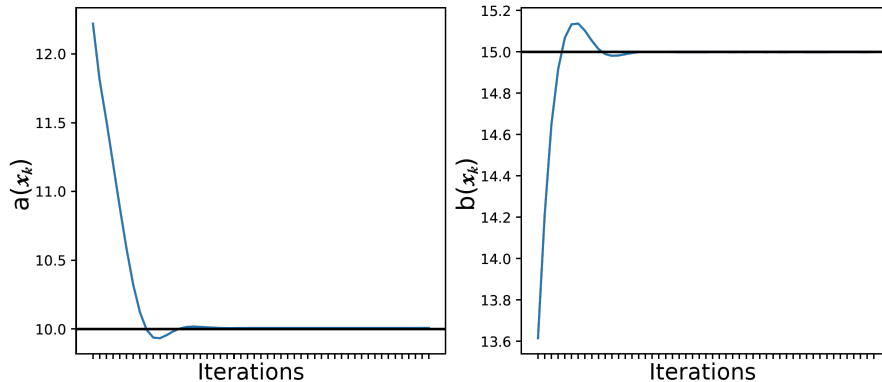
Elliptical cylinder of radius R, height H and wall thickness e, with a pressure P within



Algorithm convergence

Application - Elliptical artery II

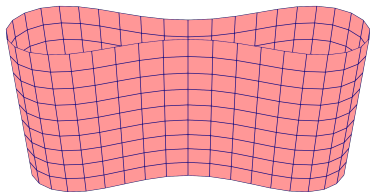
Problème inverse



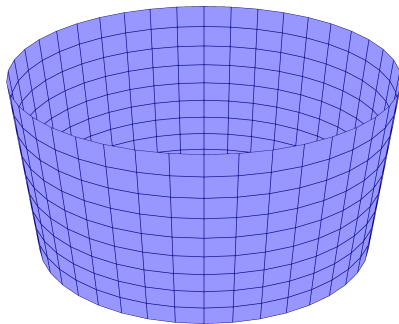
Ellipse parameters in the deformed state

Application - Elliptical artery II

Problème inverse



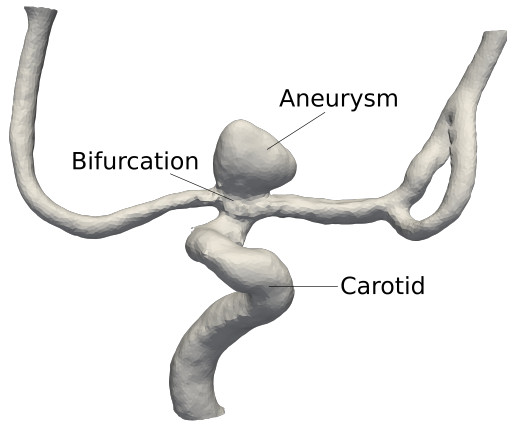
Now well-known initial state, " X^* "
not an ellipse



Deformed state, " x_m "
eccentricity $e \simeq 0.745$

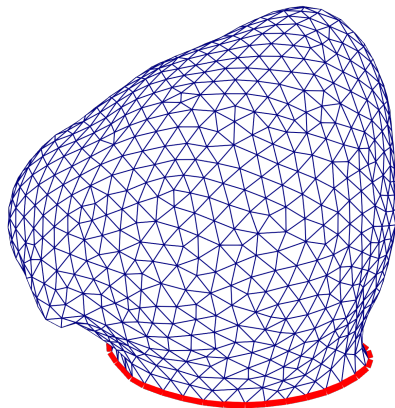
Results of the algorithm for the deformed elliptical artery

Application - patient specific aneurysm I



First example of patient specific aneurysm

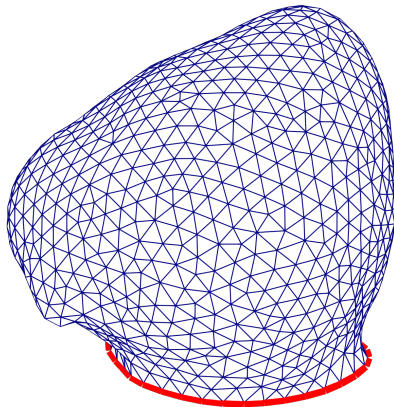
Application - patient specific aneurysm I



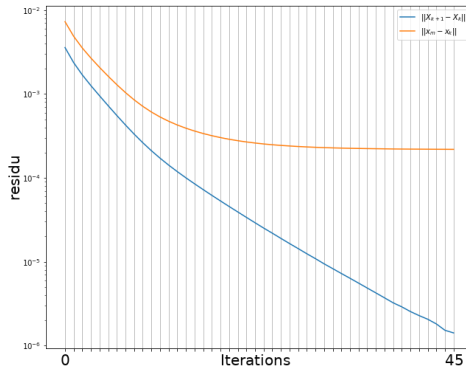
Extracted aneurysm

- ▶ Soft hyperelastic material from *Biomechanical wall properties of human intracranial aneurysms resected following surgical clipping*, V. Costalat et al. (2011)
- ▶ Imposed homogeneous pressure, with values obtained from *Monitoring the injured brain: ICP and CBF*, Steiner L.A. et al. (2006)
- ▶ No displacements of the neck outline

Application - patient specific aneurysm I

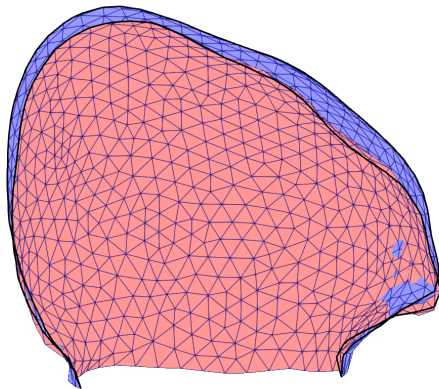


Extracted aneurysm



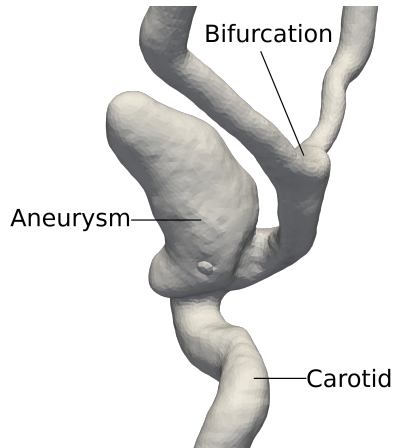
Algorithm convergence

Application - Elliptical artery I



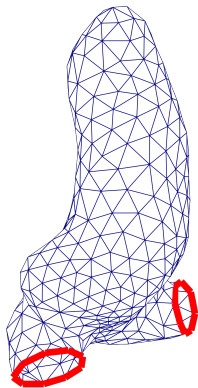
Cut view of the result of the algorithm for the patient specific aneurysm I
Unloaded state " X^* " in red and deformed state " x_m " in blue.

Application - patient specific aneurysm II



Second example of patient specific aneurysm

Application - patient specific aneurysm II

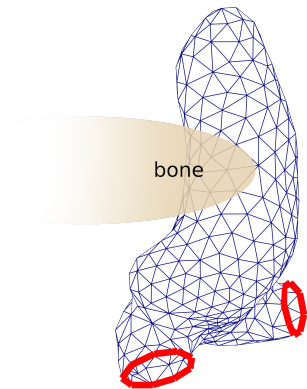


Extracted aneurysm

- ▶ Hyperelastic material from *Biomechanical wall properties of human intracranial aneurysms resected following surgical clipping*, V. Costalat et al. (2011)
- ▶ Imposed homogeneous pressure, with values obtained from *Monitoring the injured brain: ICP and CBF*, Steiner L.A. et al. (2006)
- ▶ No displacements of the artery outline

The algorithm doesn't converge.

Application - patient specific aneurysm II



Extracted aneurysm

- ▶ Hyperelastic material from *Biomechanical wall properties of human intracranial aneurysms resected following surgical clipping*, V. Costalat et al. (2011)
- ▶ Imposed homogeneous pressure, with values obtained from *Monitoring the injured brain: ICP and CBF*, Steiner L.A. et al. (2006)
- ▶ No displacements of the artery outline

The algorithm doesn't converge.

Conclusion

- ▶ Numerical iterative methods exist to find unloaded state of given geometry despite geometrical and material non linearity.
- ▶ Our contribution was to adapt such algorithm for thin elements modelization, in particular shell elements.
- ▶ Those methods depend of 2 kind of inputs:
 - ▶ the geometry which is sensible of measurement precision.
 - ▶ the material behaviour and the boundary conditions which can results in incompatibilities.
- ▶ The inverse image of a quasi-circular cylinder is not necessarily a quasi-circular cylinder.
- ▶ The inverse image of an ellipse is not necessarily an ellipse.
- ▶ For patient specific soft tissues modelization, the interaction with rigid tissues (e.g. bones) or more complex loading (non homogeneous pressure) must be taken into account to attain kinematic compatibility.
- ▶ The procurement of such unloaded configurations allow to control the influence of the anatomic structure's modelization on device deployment's computation.

Computation data

Circular and elliptic cylinders

Geometry

Circle radii $R = 10mm$
Ellipses radii $a = 10mm, b = 15mm$
Thickness $e = 2mm$

Loading

Pressure $P = 0.5kPa$

Material

Neo Hookean coefficient $C_{NH} = 2kPa$
Poisson's ratio $\nu = 0.49$

Aneurysm

Geometry

Thickness $e = 0.3mm$

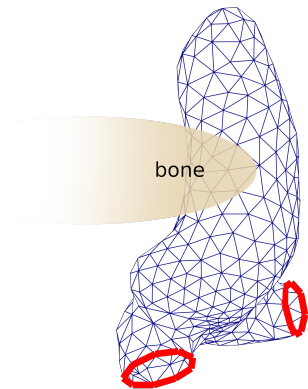
Loading

Pressure $P = 10.6kPa$

Material

Rivlin coefficients $C_{10} = 191.1kPa, C_{01} = 26.7kPa,$
 $C_{11} = 1370kPa$
Poisson's ratio $\nu = 0.49$

In vivo application - patient specific aneurysm II



Extracted aneurysm

Interactive illustration:

see <https://www.neurosurgicalatlas.com/sketchfab?id=ba43653cc29d40b1ae5febb3472f924a>