Predictive simulation for interventional neuroradiology

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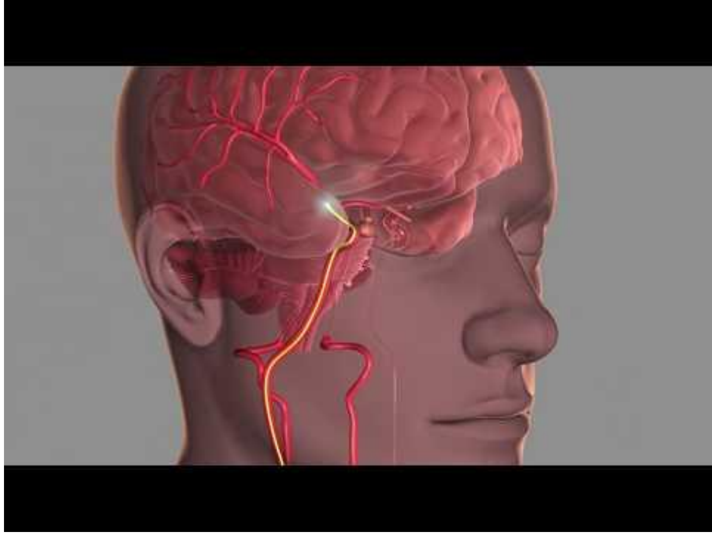
Introduction

Ischemic stroke

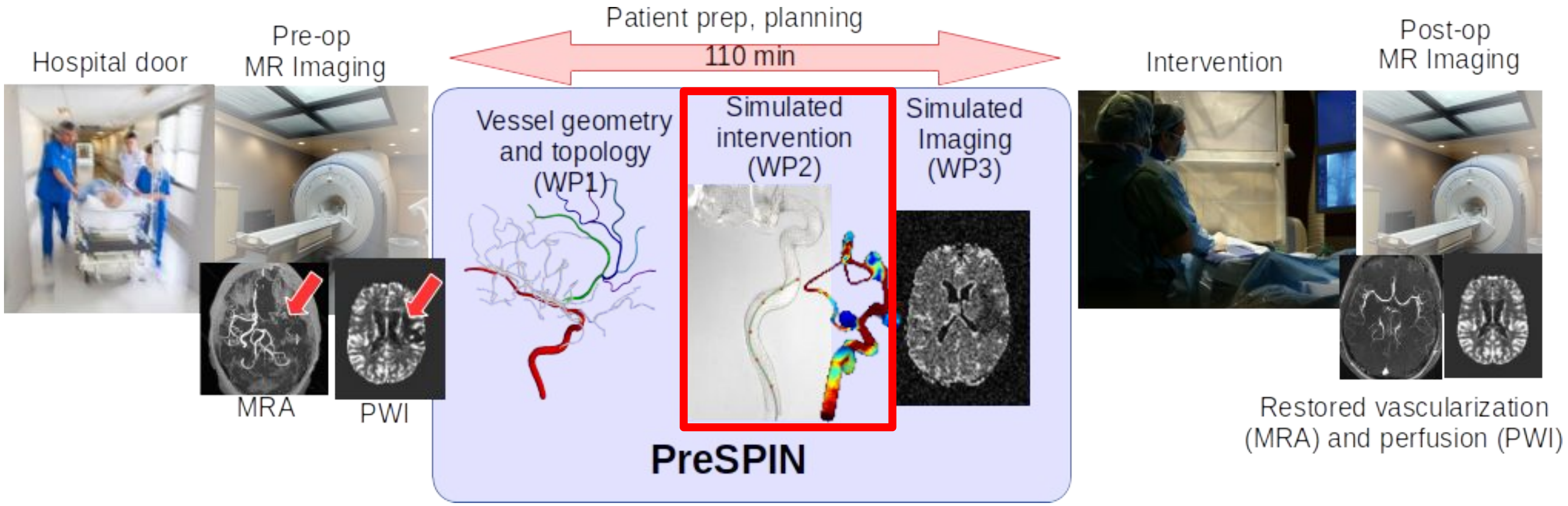
The decrease in blood flow to a part of the brain

- obstruction of blood vessels by a blood clot
  - removal of blood clots with medication
  - removal of blood clots **mechanically**
    - navigation of instruments is **challenging**
    - must be performed **within 6 hours** of stroke onset to reduce risk of disability



source: my.clevelandclinic.org

Predictive Simulation for the Planning of Interventional Neuroradiology procedures



Purpose of the thesis: predictability

There are other simulators that are realistic but not predictive:

- e.g. ANGIO Mentor

Predictability is about faithfully reproducing important events

Create a predictive simulation of mechanical thrombectomy using highly accurate

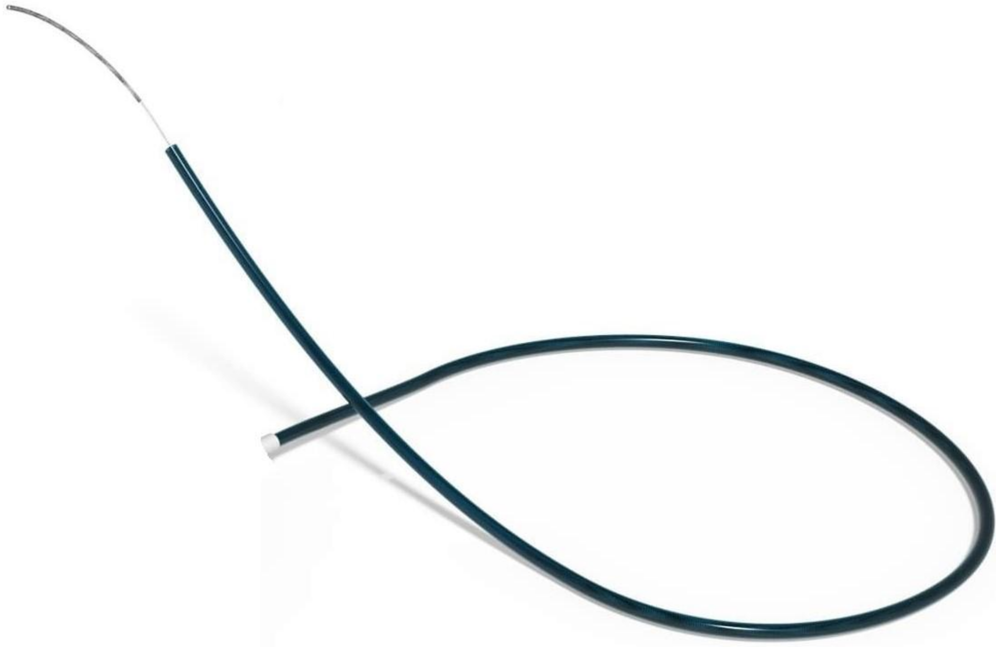
- blood vessels surface
- catheter model

and develop a new **contact model**

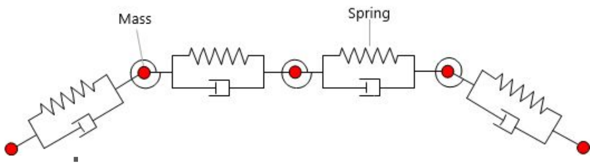
State of the art

Catheters: wire-like structures

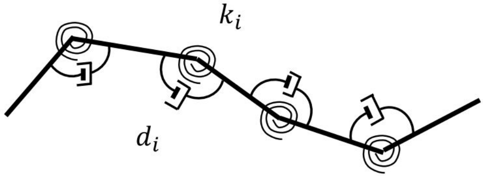
- Long, thin and deformable
- High tensile strength
- Low resistance to bending
- Geometrically non-linear



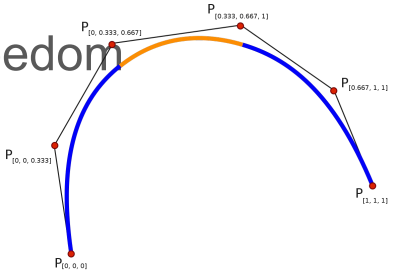
Catheter models



- Mass-spring
  - particles linked with massless linear and angular springs



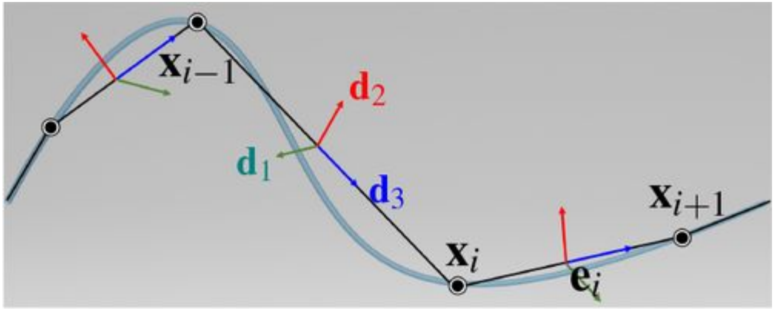
- Rigid articulated bodies
  - set of rigid elements connected using spherical joints



- Splines
  - continuous representation
  - some articles consider control points as the degrees of freedom

- Run at interactive rate
- Deformations are **not physically exact**
- Difficult to precisely tune for some given material

Catheter models



Cosserat rods

- *Set of oriented frames*
- *Length >> radius*
- Mechanically exact
- Accurately handle complex deformations
  - bending, torsion, stretching and shearing

Spillmann et Teschner 2007

Contact: penalty-based method

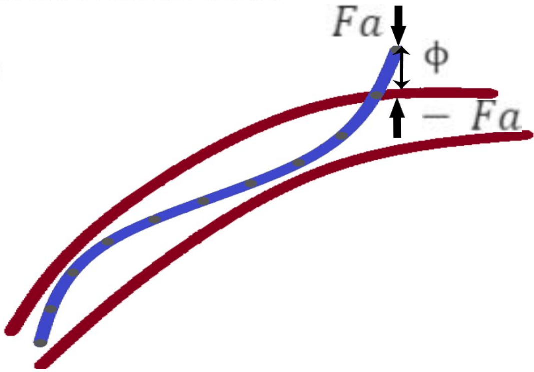
A system of spring dampers at each point of contact is used to penalize penetrations

$$Fa = (-k\phi - bv \cdot n)\, n$$

$$Fb = -Fa$$

k and b: stiffness and damping coefficients

ϕ: penetration depth



Pros:

- fast and relatively easy to implement
- easily converts a constrained problem into an unconstrained problem

Cons:

- it is not trivial to choose the stiffness and damping parameters
- the stiffness parameter must be large enough to eliminate penetration, but setting it too high increases the cost of the simulation

Contact: constrained-based method

Solve the constraints forces ***Fc*** and add them to the equation of motion:

$$Ma = F + Fc = F + J^T \lambda$$

λ: *Lagrange multiplier*

J: *Jacobian of the constraints*

while ensuring complementarity condition

$$0 \leq \phi \perp \lambda \geq 0$$

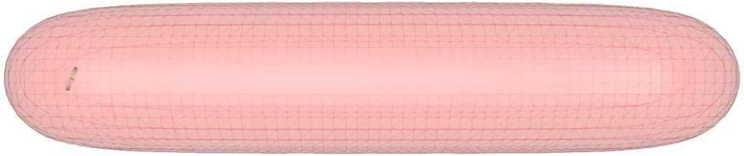
ϕ: *Gap function*

Solution: solve the linear complementarity problem, minimize $\phi \cdot \lambda$
Pros: it leads to simulations where interpenetration is completely eliminated (but due to discretization errors, stabilization is necessary)
Cons: time-consuming

Blood vessels surface

Polygonal mesh

- slow collision detection
- inaccurate collision response



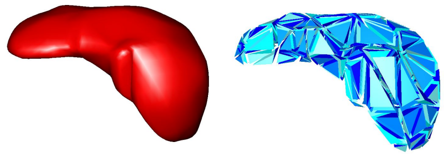
Implicit surface (e.g. Blobby Model)

- fast collision detection
- accurate collision response

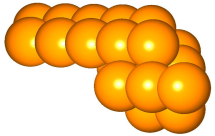
E.Kerrien et al. 2017

Evaluation of a simulation

SOFA Framework

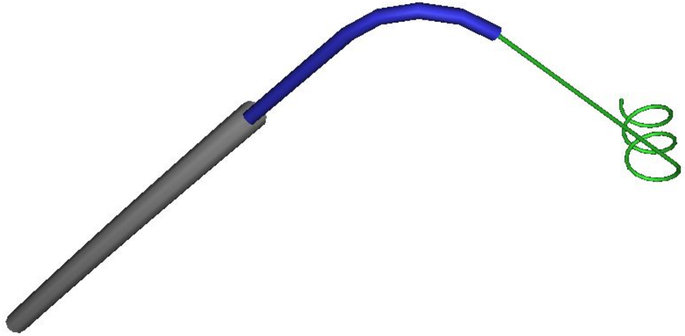


Open source framework for medical simulations



Catheter model:

- beam theory (actual mechanical parameters)
- includes translations and rotations
- configurable resting shape



Contact model:

- polygonal mesh
- LCP constraint solver
- Euler implicit solver

Catheter experience

Three different scenarios

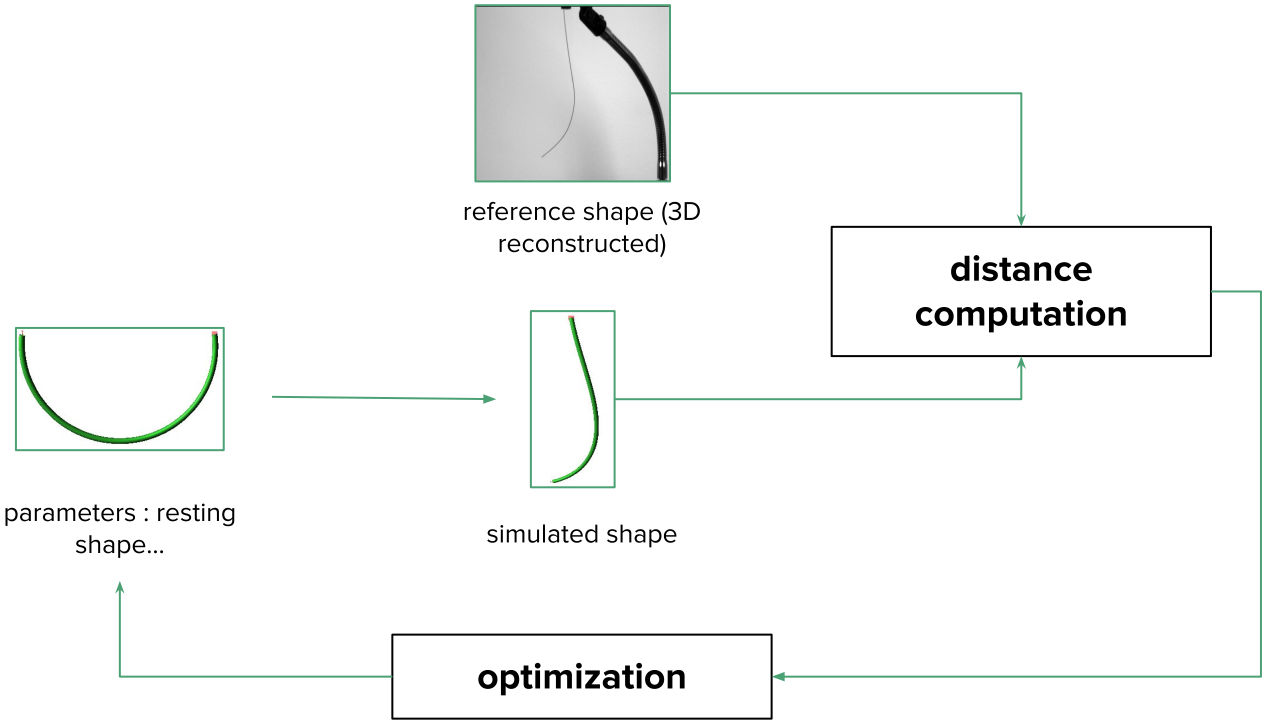
1. tip attached
2. translations and rotations
3. insertion inside a phantom

Materials

- two cameras
- a robot executing translations and rotations
- a phantom forming blood vessels

The output is a sequence of 3D reconstructed points

The chosen approach: geometric evaluation

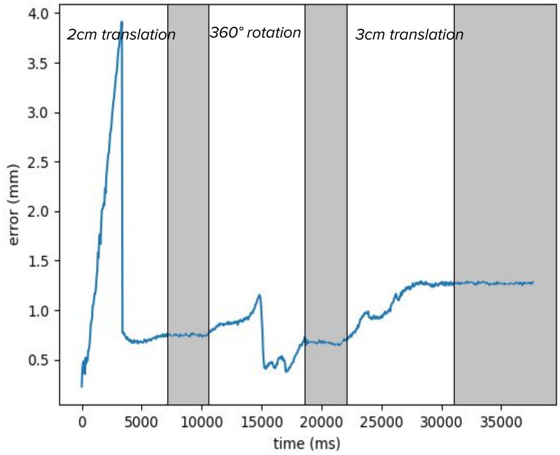


Results

1. tip attached (without contacts)
   - ➢ length = 31 cm
   - ➢ error = **3.35 mm**

2. translations and rotations (without contacts)
   - ➢ length goes from 0 to 5 cm
   - ➢ error is between **0.5 to 1.5 mm**

3. insertion inside a phantom (with contacts)
   - ➢ the catheter **exits the surface**



Conclusion

This mechanical model cannot be used for prediction

- we have chosen to use a physically correct cosserat

Contact model is inaccurate

- we will propose a new contact model that uses implicit surfaces

Thank you