# Medical Robotics

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# Needle insertion supported by robots

We will see how robot can help in addressing issues related to insertion of needle (diagnostic and terapeutic purposes) in percutaneous procedure. The main challenges are the  geometrical constraints imposed by the environment that is very narrow.


SAPIENZA
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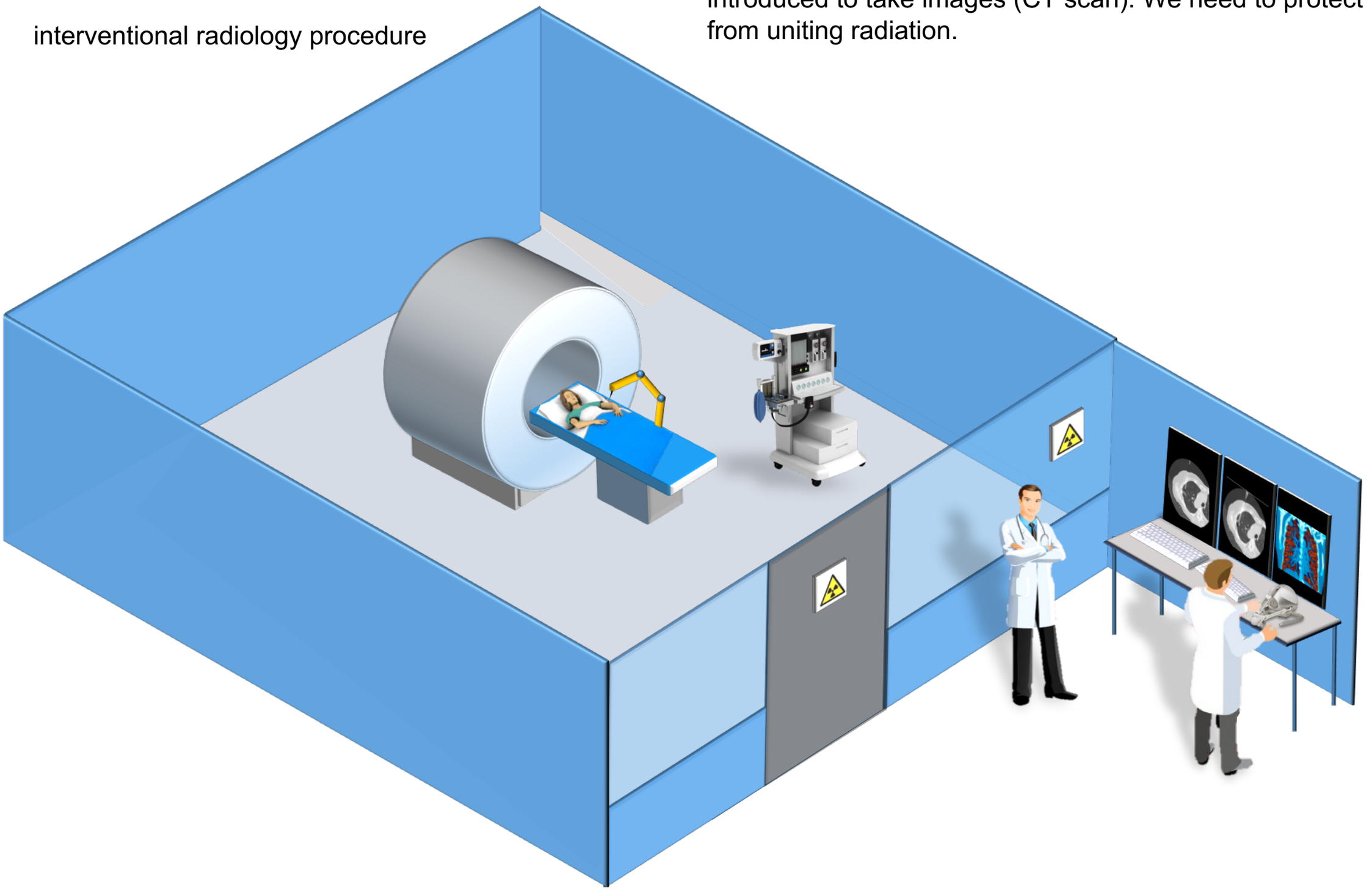
# a conceptual scheme

interventional radiology procedure

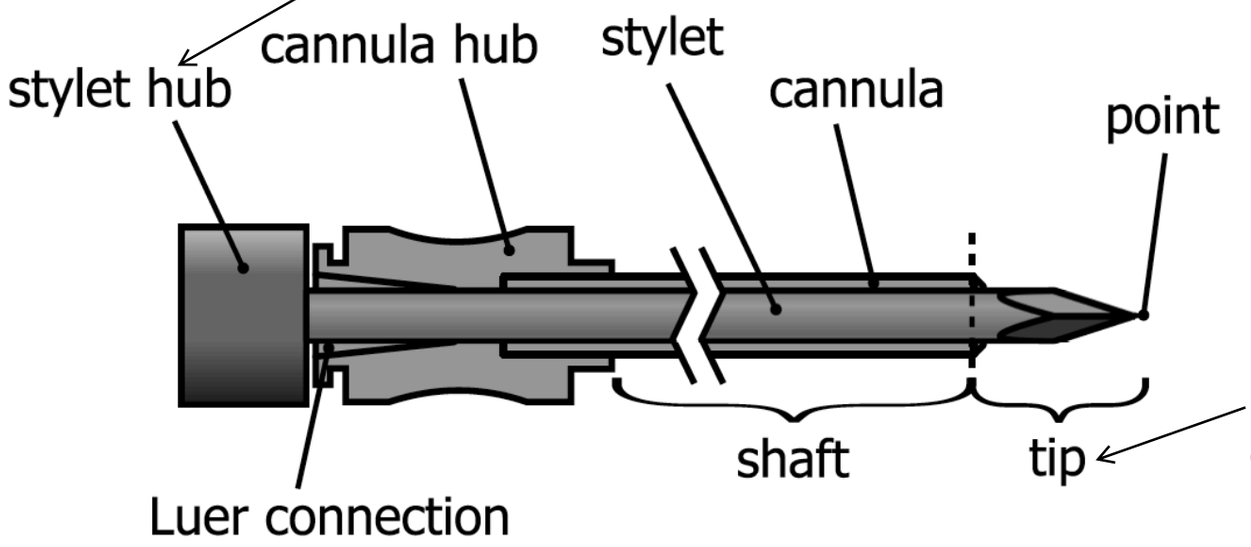
the patient is isolating inside the operating room where we have the imaging system (in this case this is more close to the RM device imaging system) because of the narrow environment in which the patient is introduced to take images (CT scan). We need to protect the operator from uniting radiation.



We focus on the mechanic needle-tissue interaction.

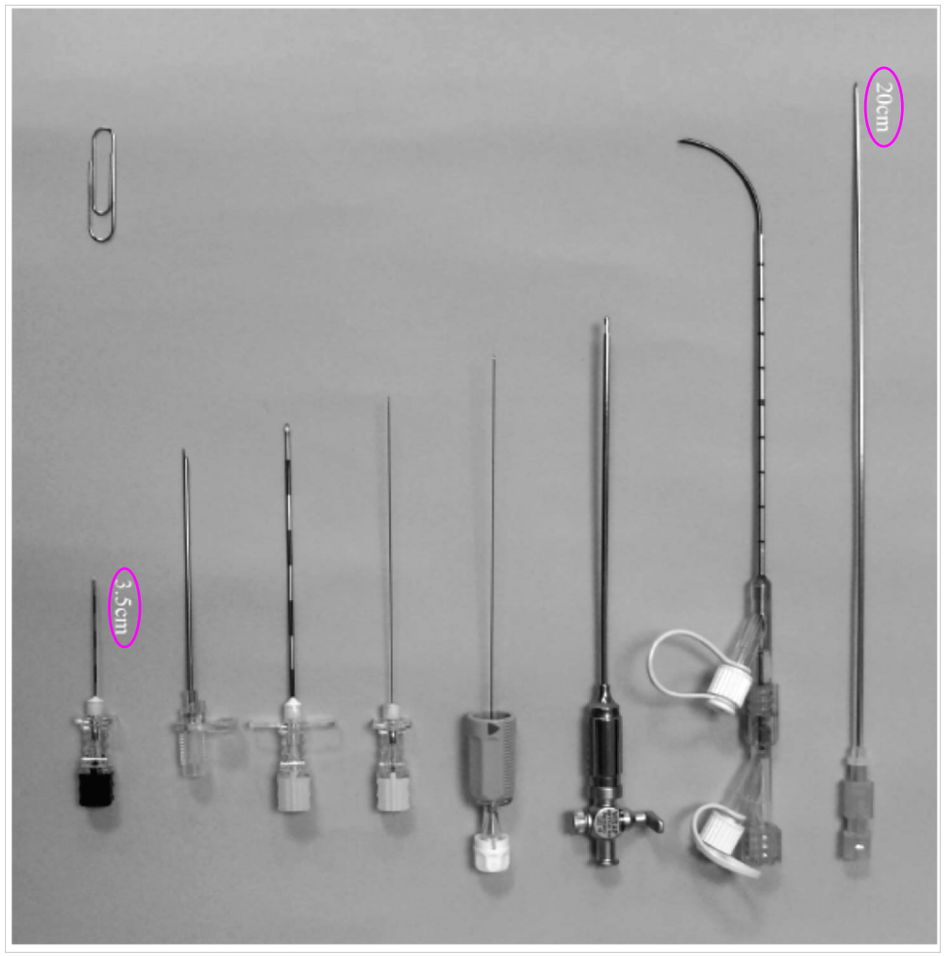
# Needles

It is connected, in case of a teleoperated insertion, to the robot E-E. Through it we can insert the cannula.




## main components

It can be of different type, the shape of the interaction depends on the shape of the needle




an assortment of needles
from intravenous cannulation
to kidney catheterization

# Needle tips

Franseen (triangular) needle
(needle with symmetric tip)

also called trocar with diamonds tip

important characteristic

Conic tip needle
(needle with symmetric tip)

Bevel tip needle (22°)
(needle with asymmetric tip)

the interaction between needle and tissue makes the needle curve when traversing the tissue. The force of the needle tip is different from the force of the needle shaft

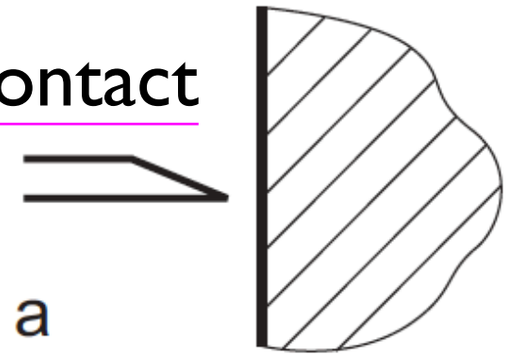
Bevel tip needle (45°)
(needle with asymmetric tip)

the different angles have different result on the cut when the needle interact with tissue and so also on the forces exchanged

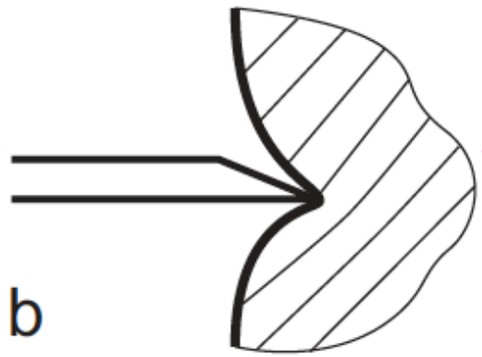
Blunt tip needle (90°)

# Needle insertion phases

4 phases

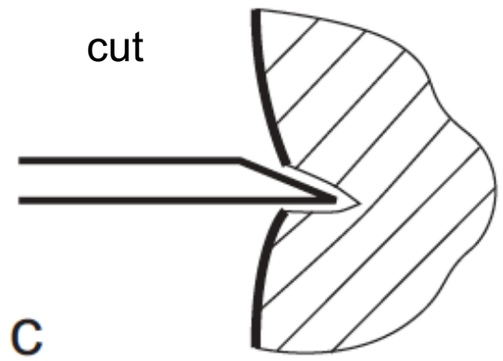



no contact



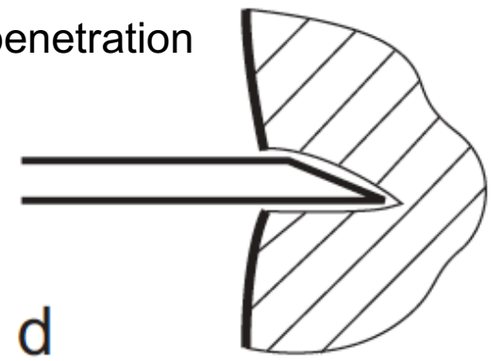

deformation

contact with boundary displacement displacement of the tissue



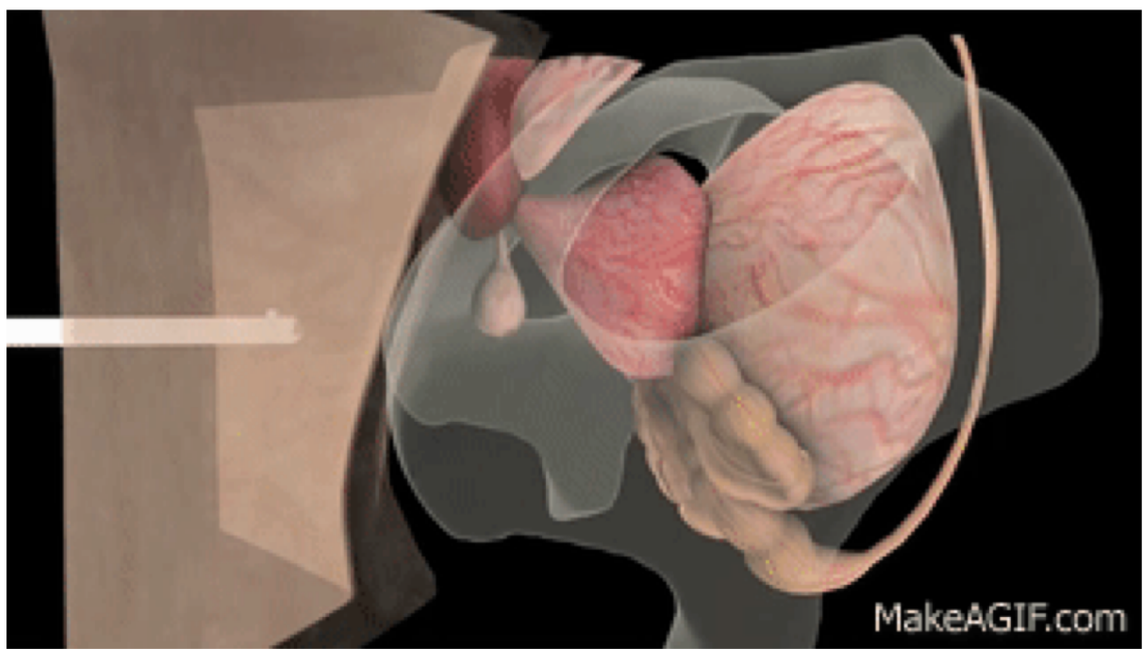

cut

tip insertion




penetration

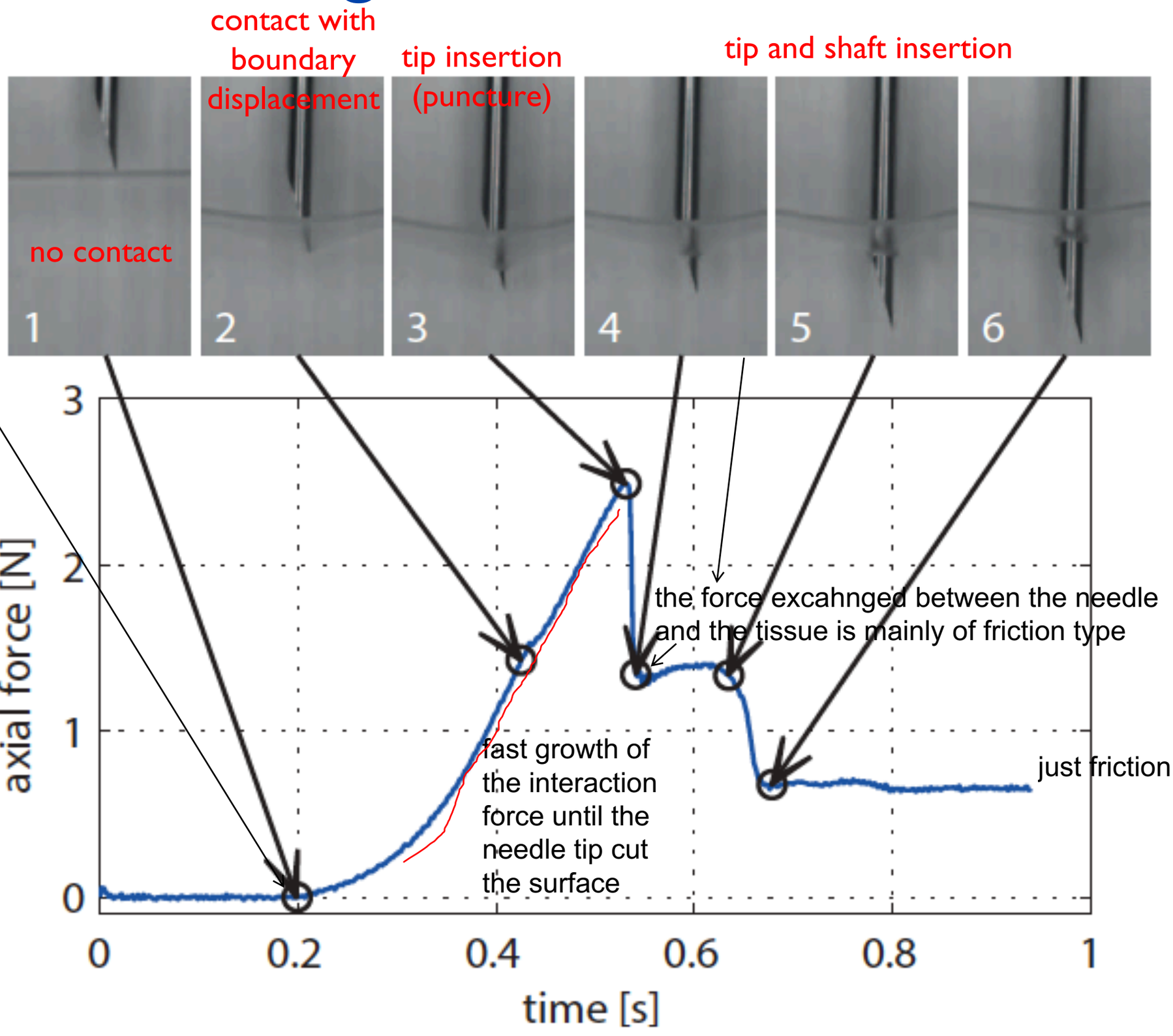
tip and shaft insertion



# Axial force during insertion

forces measured along the axis of needle shaft.

when there is no contact, the exchanged force is equal to zero

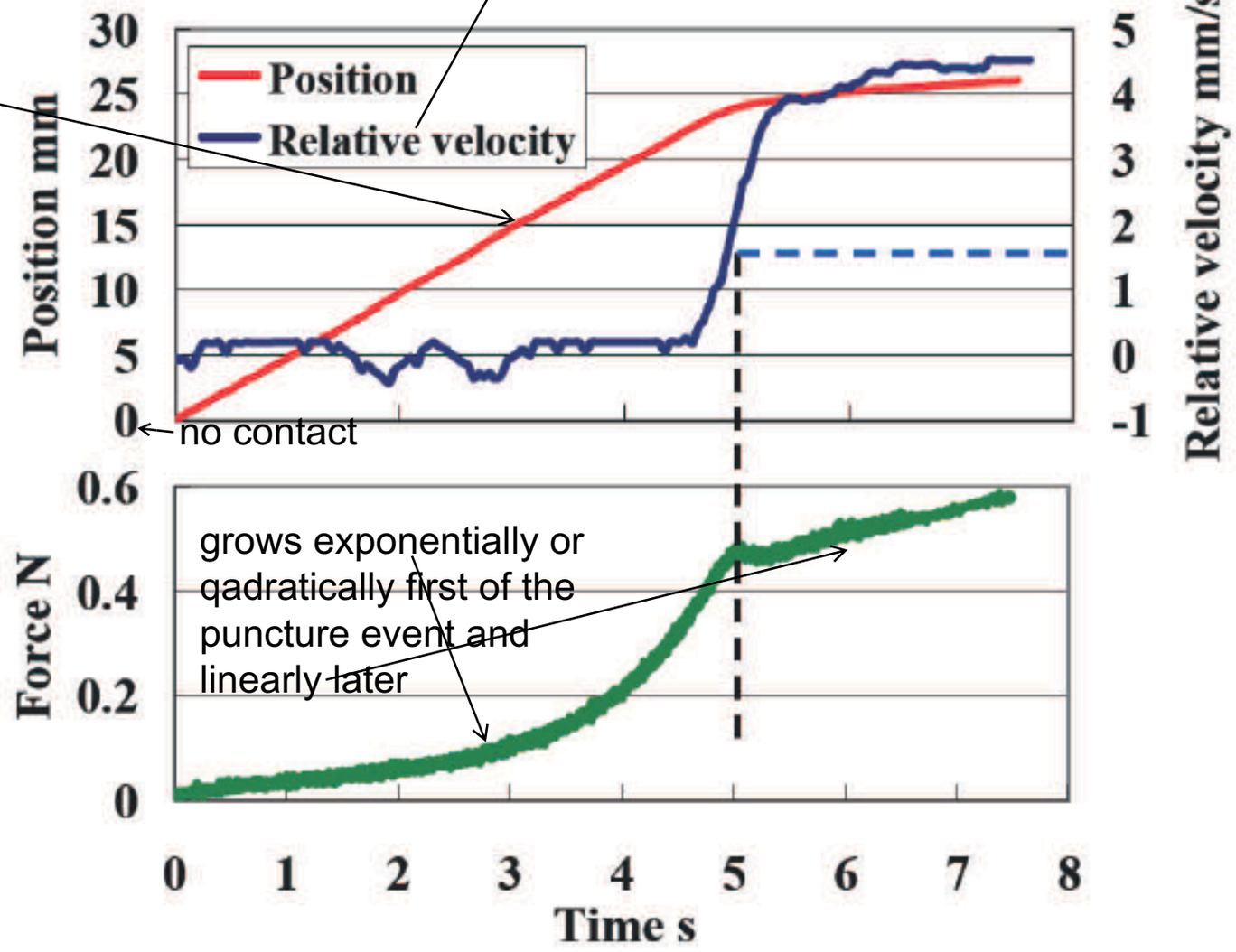


it not happens only at the beginning when the needle is introduced in the skin, but very often the operator makes small incisions on the skin to avoid these initial elestic forces exchanged.

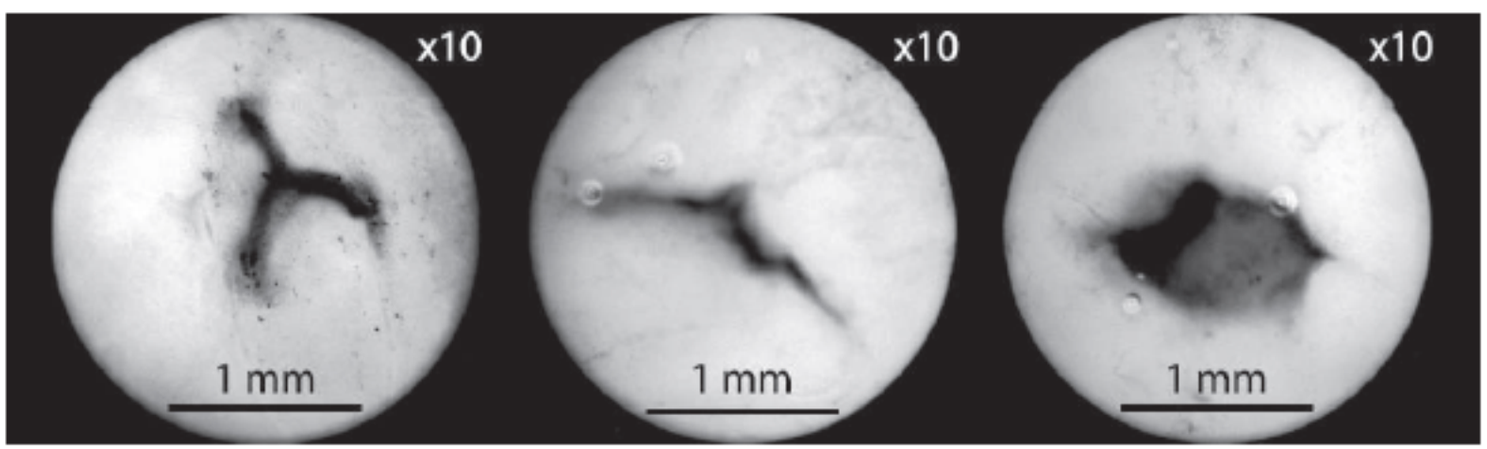
# Puncture event

when the position displacement grows linearly the relative velocity is zero. It means that the puncture event is not happen yet

between the needle tip and the tissue




pre- and post-puncture tissue position and relative velocity and interaction force

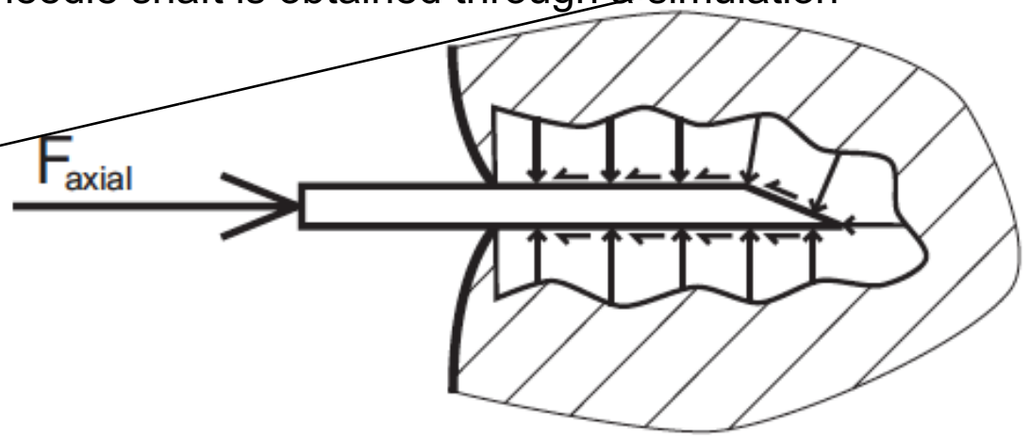



crack shape and tip type (diamond, small bevel angle, large bevel angle)

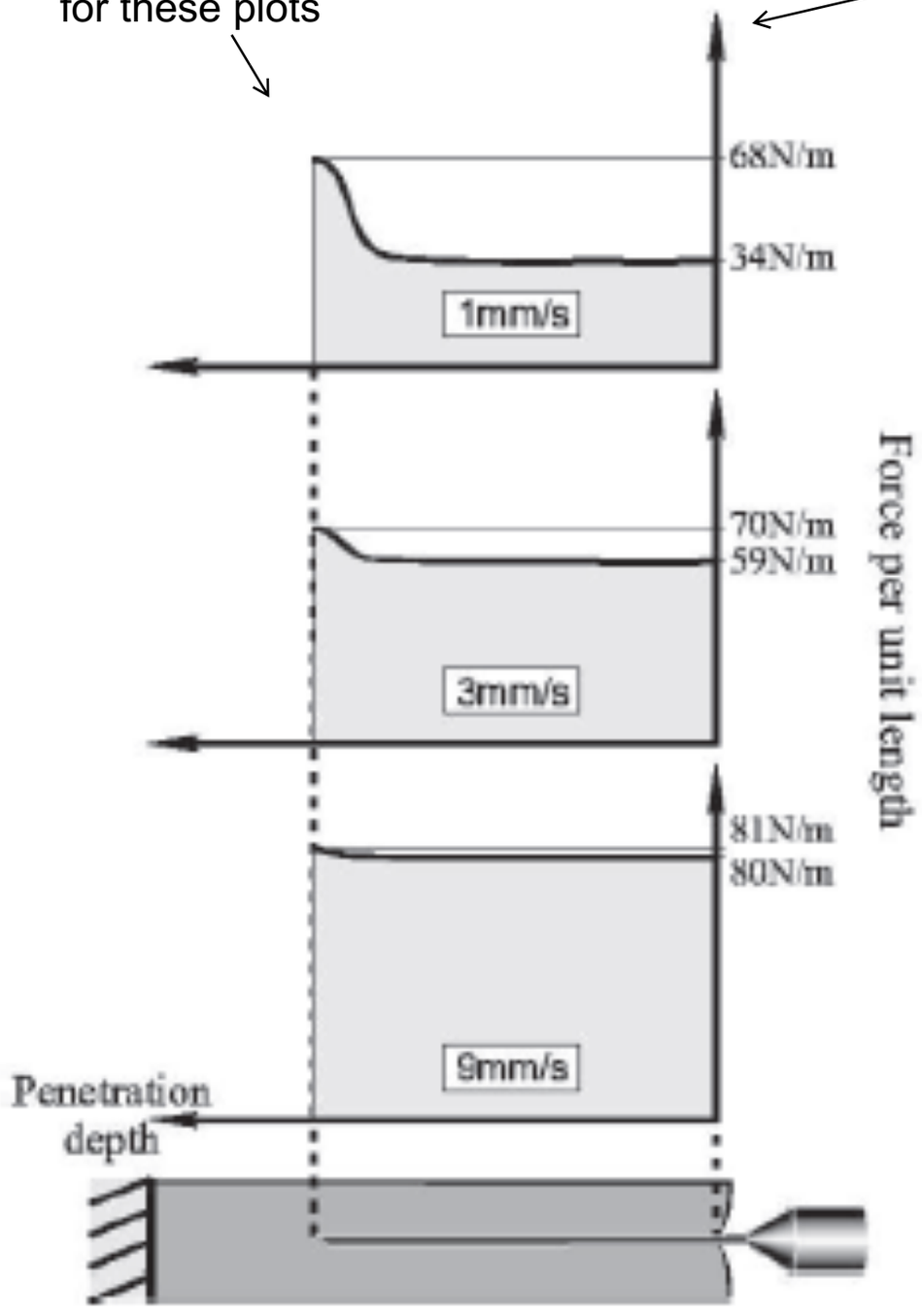
90°

# Load distribution

Forces exchanged between the needle and the tissue. We have both tangential forces (all around the needle shaft) and normal forces. The distribution of these forces along the needle shaft is obtained through a simulation

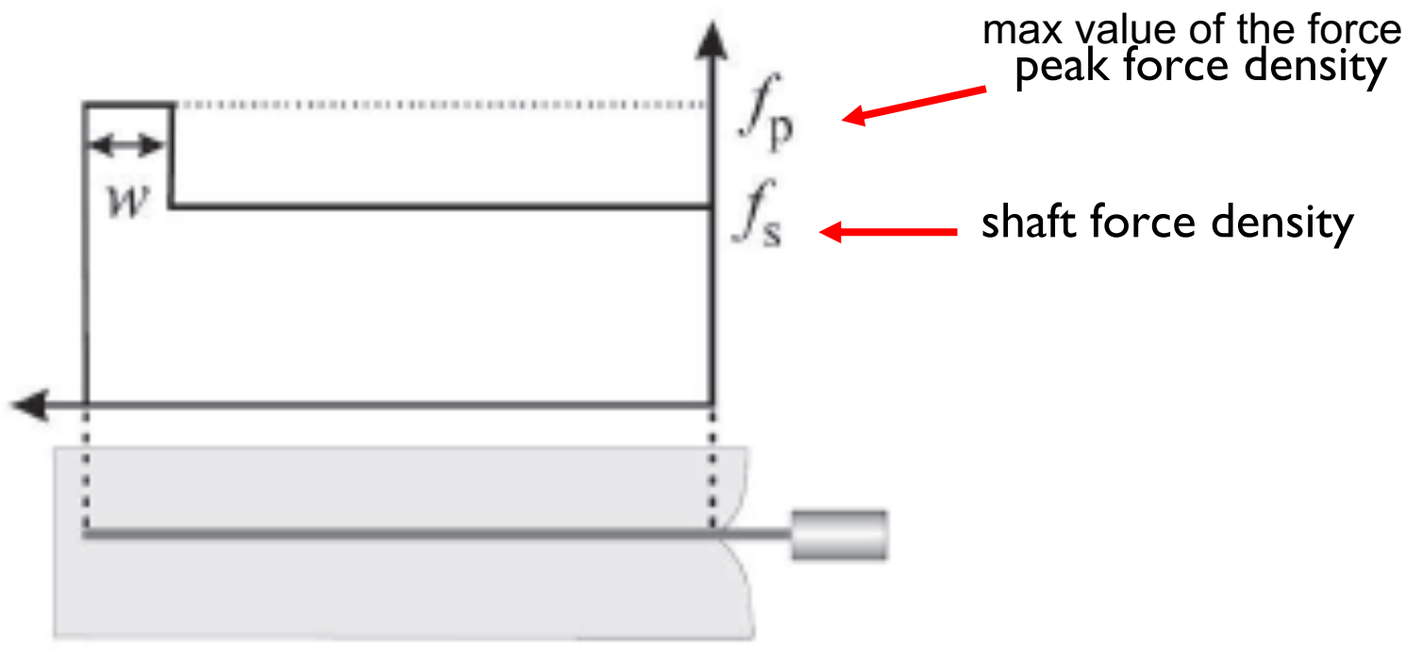



different insertion velocity for these plots



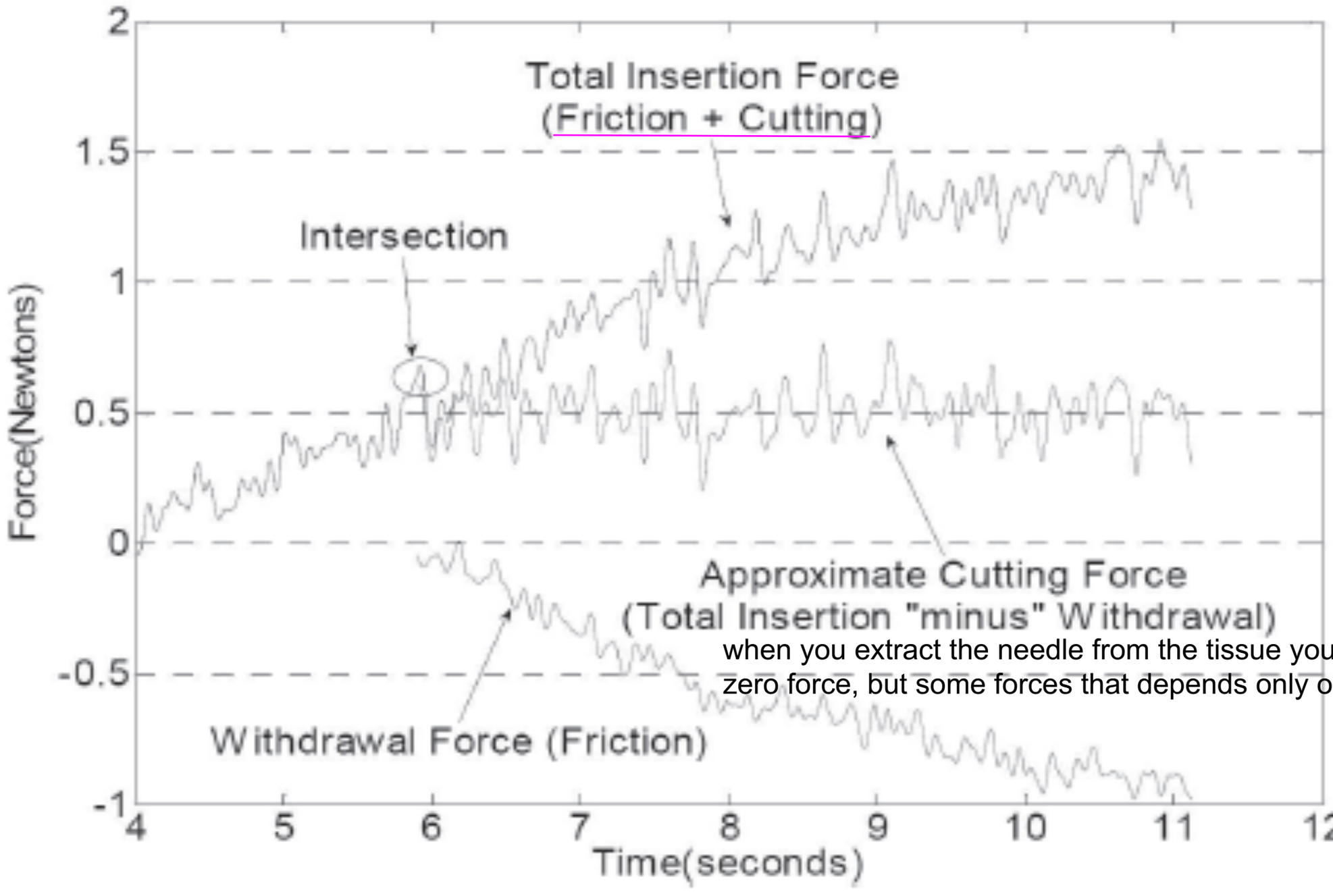

force density depends on the velocity

distribution of tangential and normal forces along the needle shaft (PVC phantom) approximately uniform both for artificial and biological tissues



# Cutting force

penetration force is made up of elastic and friction force with the component of cutting force that still is presentwhile the needle is penetrating inside the tissue.

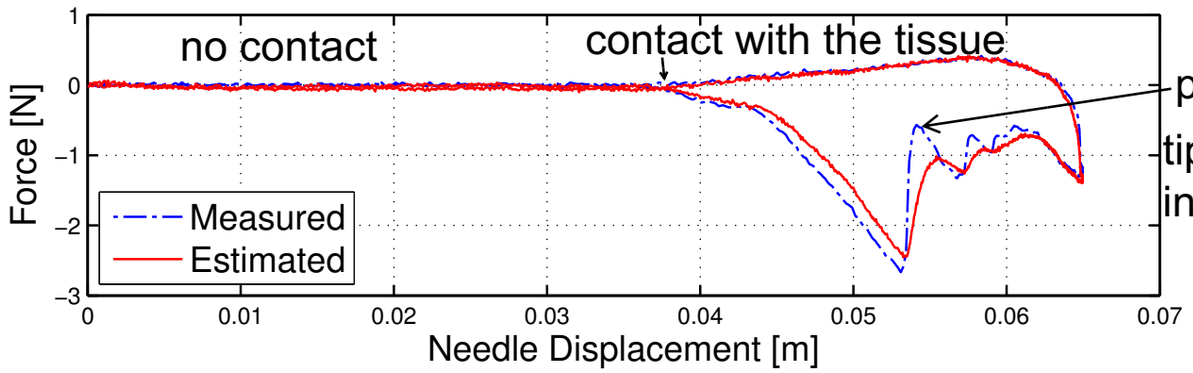



when you extract the needle from the tissue you will measure no zero force, but some forces that depends only on the friction

# Influence of insertion method

it is important

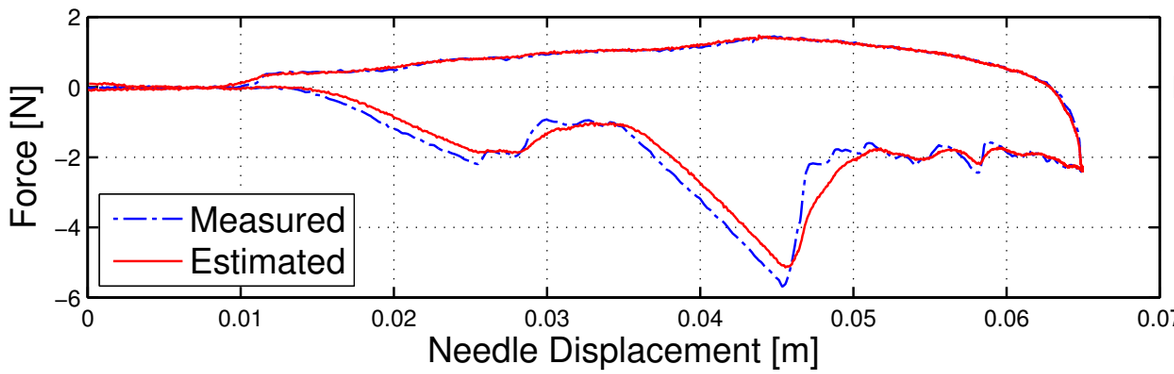
experiment in which the needle is moved by KUKA robot along the sinusoidal trajectory




puncture event (cut)

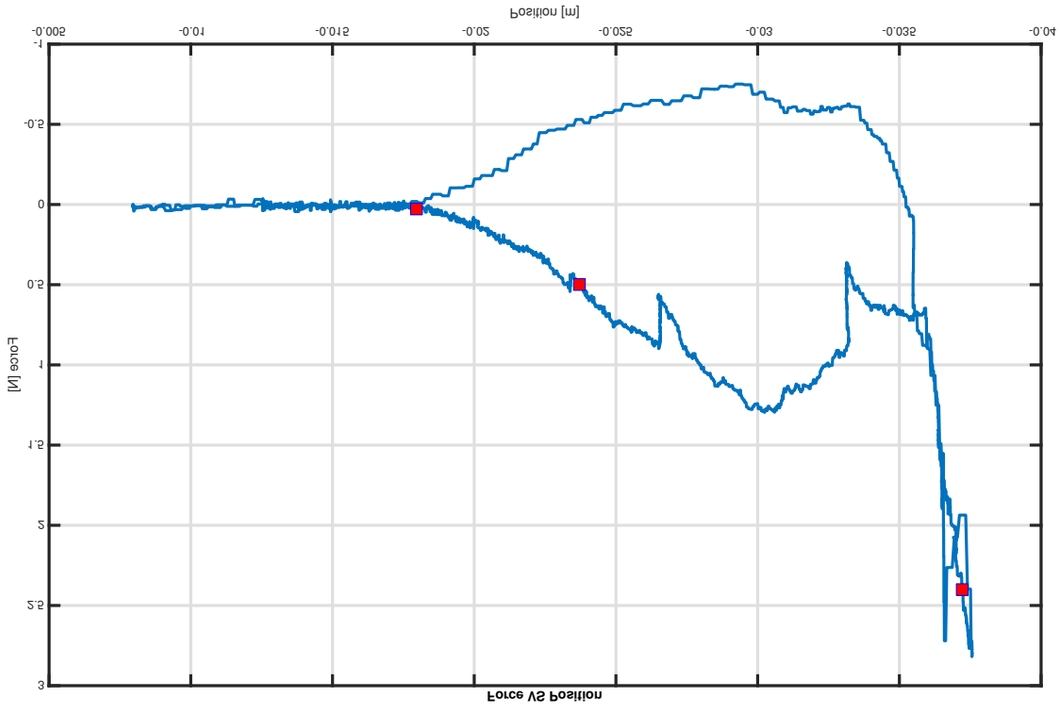
tipical shape of needle-tissue interaction forces in consequence of insertion and extraction motion

robotic

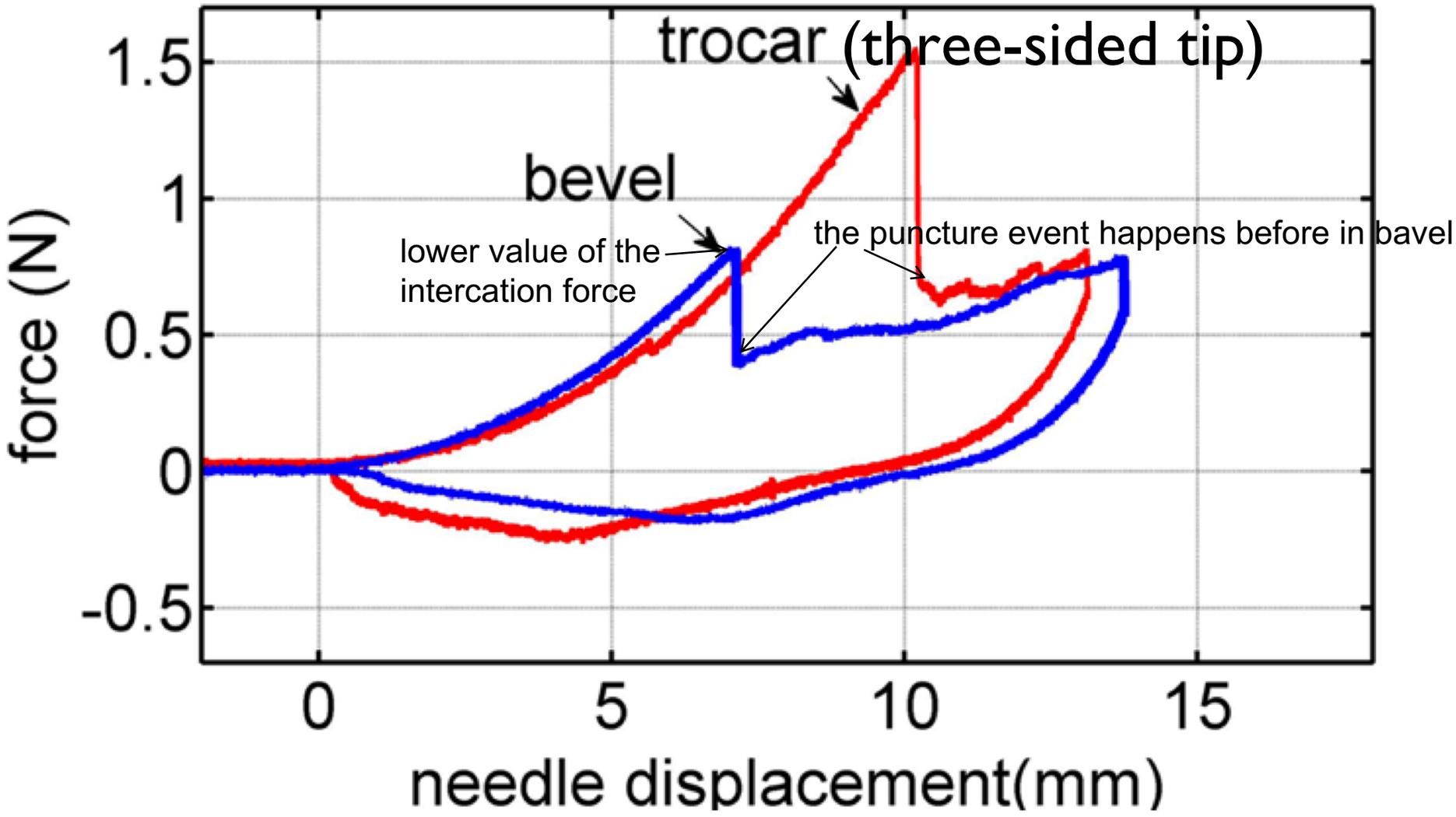



muscle and connected tissue (not skin)

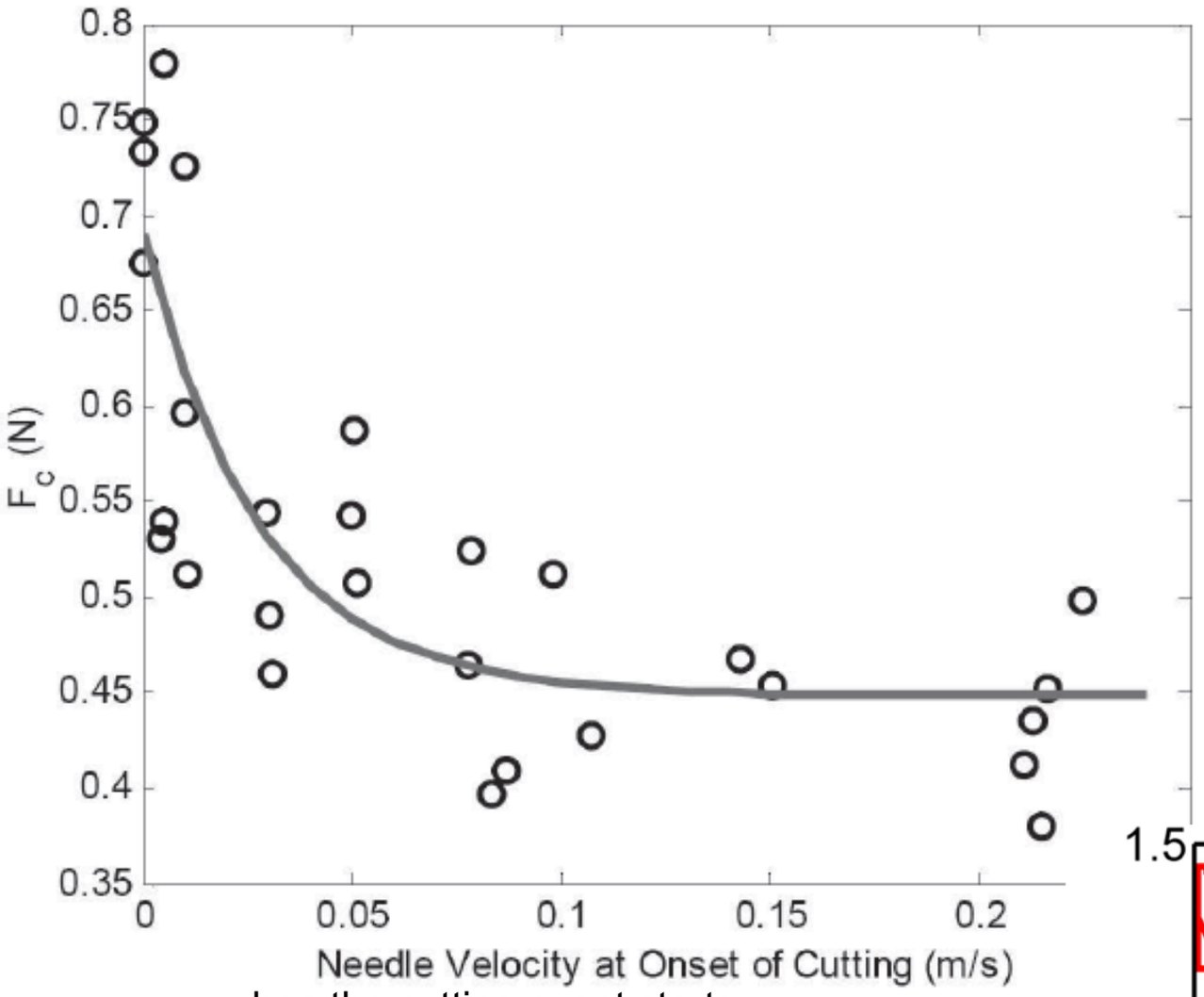
manual



# Influence of needle type



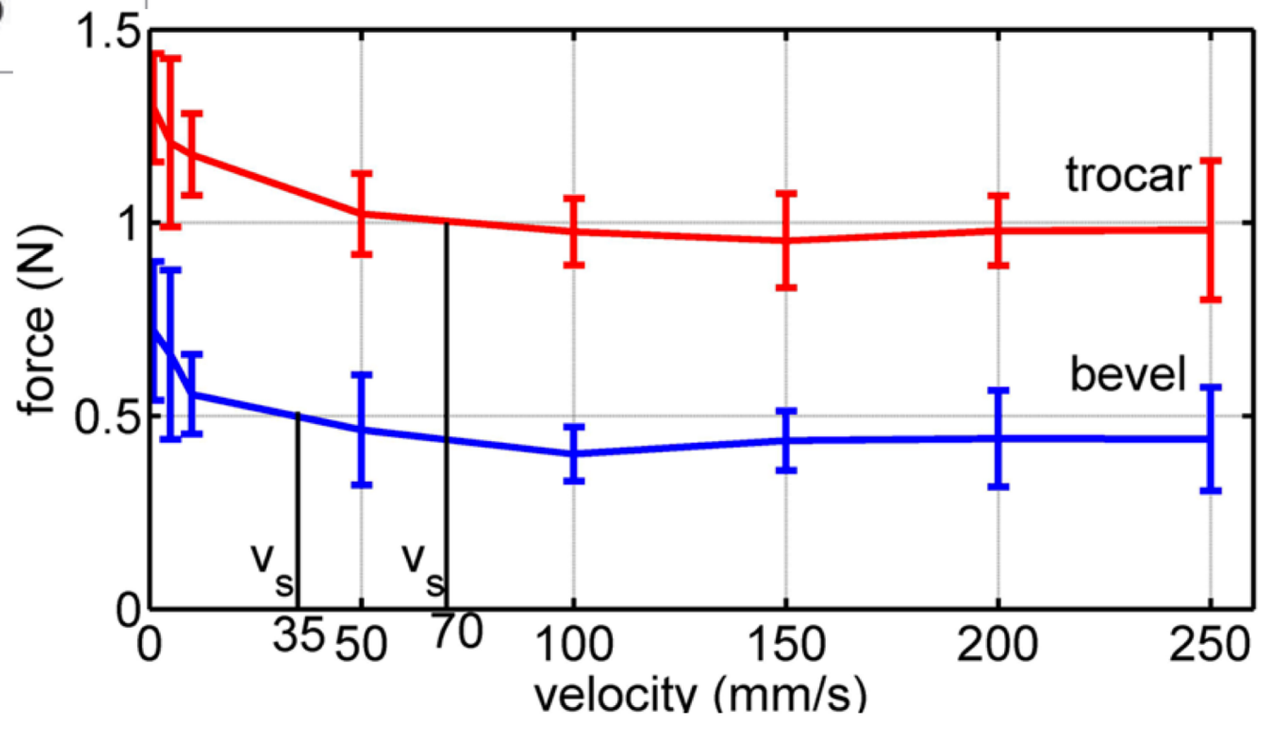
# Influence of insertion velocity



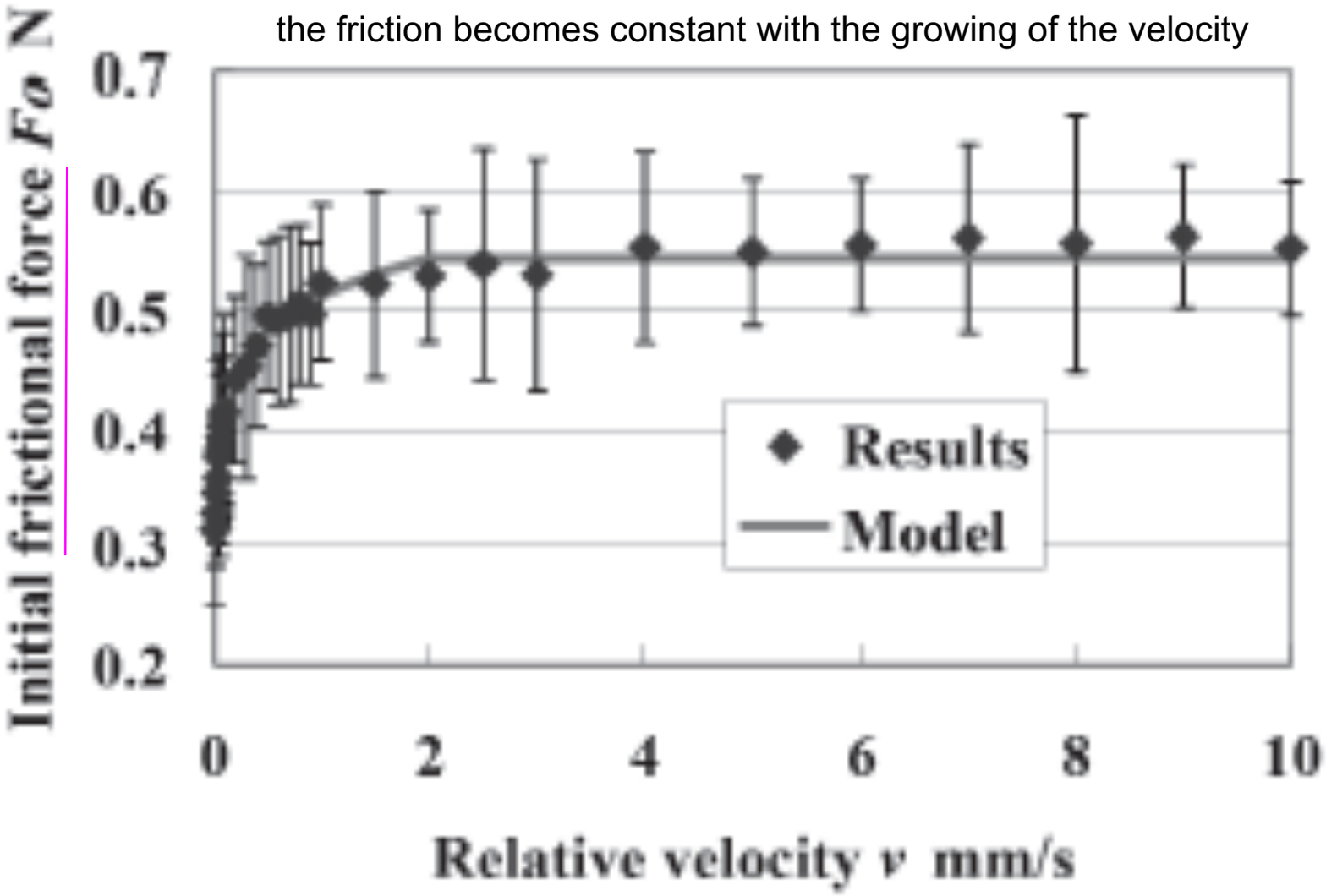

when the cutting event starts

puncture force
(diamond tip,
porcine heart, epicardial layer)

mean peak axial force
(porcine heart muscle)



# Influence of insertion velocity



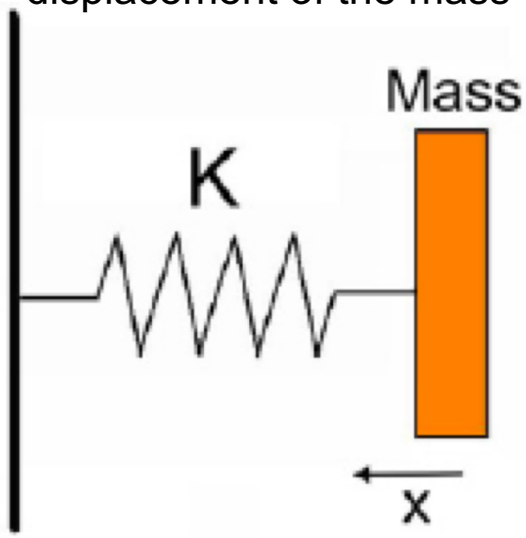

friction force vs insertion velocity (porcine liver)

# Other variables influencing the axial force

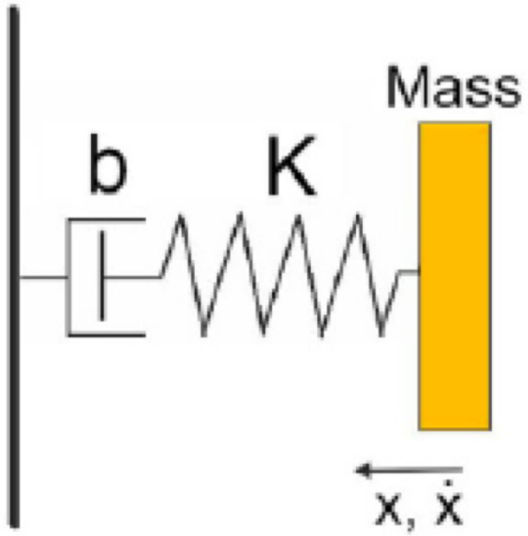
- tissue characteristics (artificial vs biologic, human vs animal, dead vs living, etc.)
- axial rotations
- insertion location and direction
- bevel orientation
- lubrication
- decay time
- ..

# Contact models: single layer

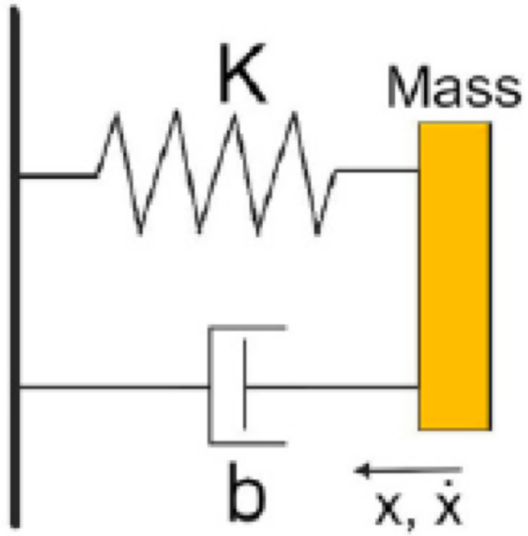
the force depends only on the displacement of the mass



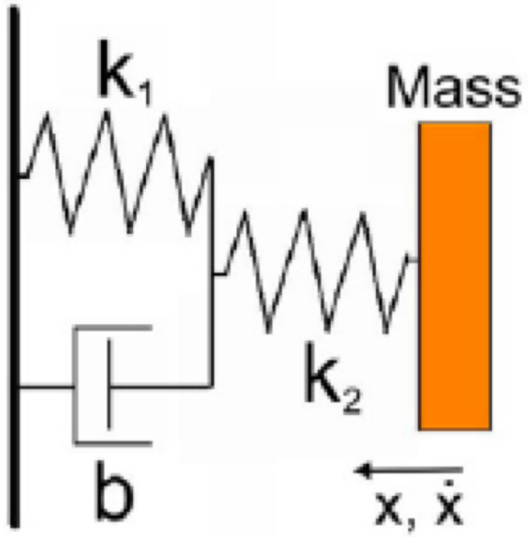

elastic




Maxwell

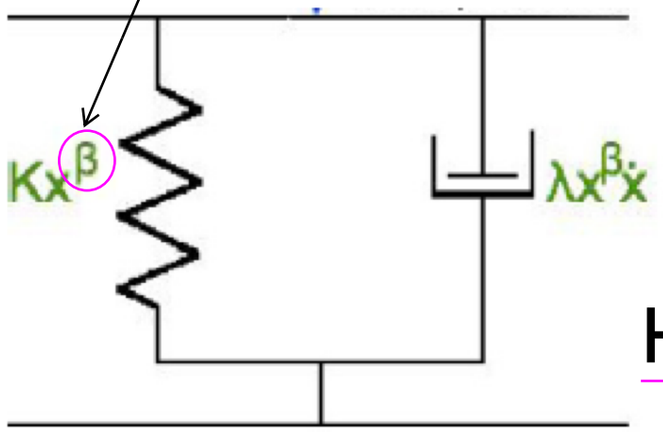



Kelvin-Voigt

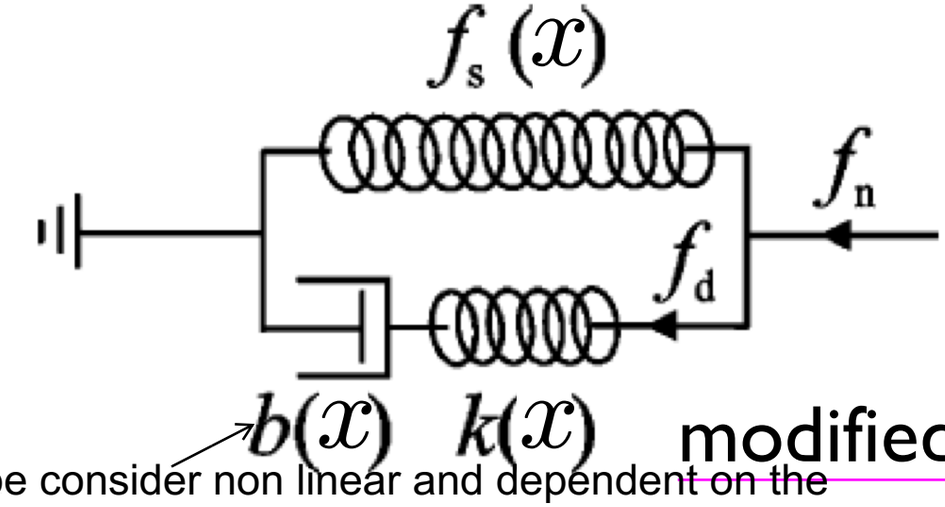



Kelvin-Boltzman

establish the order of the model




Hunt-Crossley




modified Kelvin

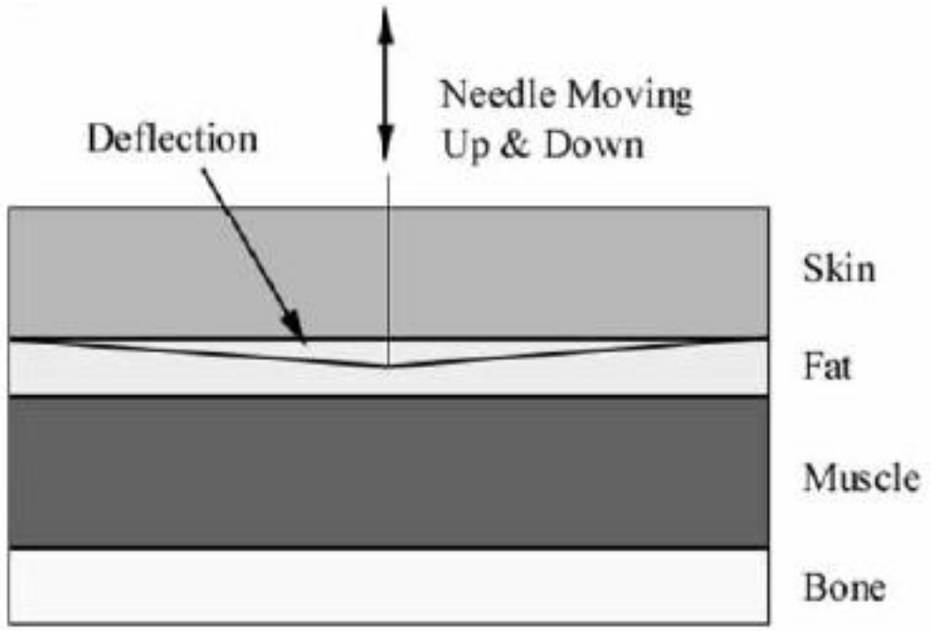
it can be consider non linear and dependent on the displacement x of the tissue

# Contact models: single layer

| Model | Equation |
|---|---|
| Elastic | $f(t) = k \cdot x(t)$ |
| K. Voigt | $f(t) = k \cdot x(t) + b \cdot \frac{x(t)}{dt}$ |
| K. Boltzmann | $f(t) = \beta x(t) + \alpha \frac{x(t)}{dt} - \gamma \frac{f(t)}{dt}$ |
| Maxwell | $f(t) = k \cdot x(t) + \alpha \cdot \frac{f(t)}{dt}$ |
| Hunt–Crossley | $f(t) = k \cdot x^n(t) + \lambda \cdot x^n(t) \cdot \frac{x(t)}{dt}$ |

# Multi-layer interaction force model

the needle has to go into different layers




SKIN

$$F = \begin{cases} k_s y & \text{upon contact} \\ b_s y v & \text{after puncture} \end{cases}$$

velocity of the needle

FAT

$$F = \begin{cases} k_f y + b_s y_s v & \text{upon contact} \\ (b_s y_s + b_f y)\, v & \text{after puncture} \end{cases}$$

MUSCLE

$$F = \begin{cases} k_m y + (b_s y_s + b_f y_f)\, v & \text{upon contact} \\ (b_s y_s + b_f y_f + b_m y)\, v & \text{after puncture} \end{cases}$$

elastic force due to the interaction between the boundary of that layer + force of penetration inside all the prevoius layers

mainly friction but also some cutting force

BONE

$$F = k_b y + (b_s y_s + b_f y_f + b_m y_m)\, v \quad \text{upon contact}$$

# Online parameters identification

classical viscoelastic model

- Needle-tissue interaction force model for identification: Kelvin-Voigt (KV) model

linear model but not necessary time invariant

$$f(t) = -K(t)p(t) - B(t)\dot{p}(t) = \boldsymbol{\varphi}(t)^T\boldsymbol{\theta}(t) \qquad \boldsymbol{\varphi}(t) = \begin{pmatrix} -p(t) & -\dot{p}(t) \end{pmatrix}^T, \quad \boldsymbol{\theta}(t) = \begin{pmatrix} K(t) & B(t) \end{pmatrix}^T$$

- Online Parameters identification (RLS with covariance resetting)

similar to identification problem

$$\hat{\boldsymbol{\theta}}_k = \begin{pmatrix} \hat{K}_k \\ \hat{B}_k \end{pmatrix} = \hat{\boldsymbol{\theta}}_{k-1} + \frac{\boldsymbol{\Psi}_{k-1}\boldsymbol{\varphi}_k e_k}{\lambda_k + \boldsymbol{\varphi}_k^T\boldsymbol{\Psi}_{k-1}\boldsymbol{\varphi}_k}$$

Par. Estimate

$$\boldsymbol{\Psi}_k = \boldsymbol{\Psi}_{k-1} - \frac{\boldsymbol{\Psi}_{k-1}\boldsymbol{\varphi}_k\boldsymbol{\varphi}_k^T\boldsymbol{\Psi}_{k-1}}{\lambda_k + \boldsymbol{\varphi}_k^T\boldsymbol{\Psi}_{k-1}\boldsymbol{\varphi}_k}$$

Covariance

in way that the algo updates the parameters

$$\hat{f}_k = \boldsymbol{\varphi}_k^T\hat{\boldsymbol{\theta}}_{k-1} \longrightarrow e_k = f_k - \hat{f}_k$$

**estimated force** **estimation error**

- Layer transitions detection based on the error function

$$s_k = e_k^2 \longrightarrow \gamma < g_k = \begin{cases} 0, & \text{if } k = 0 \\ \max(g_{k-1} + s_k - \nu, 0) & \text{otherwise} \end{cases}$$

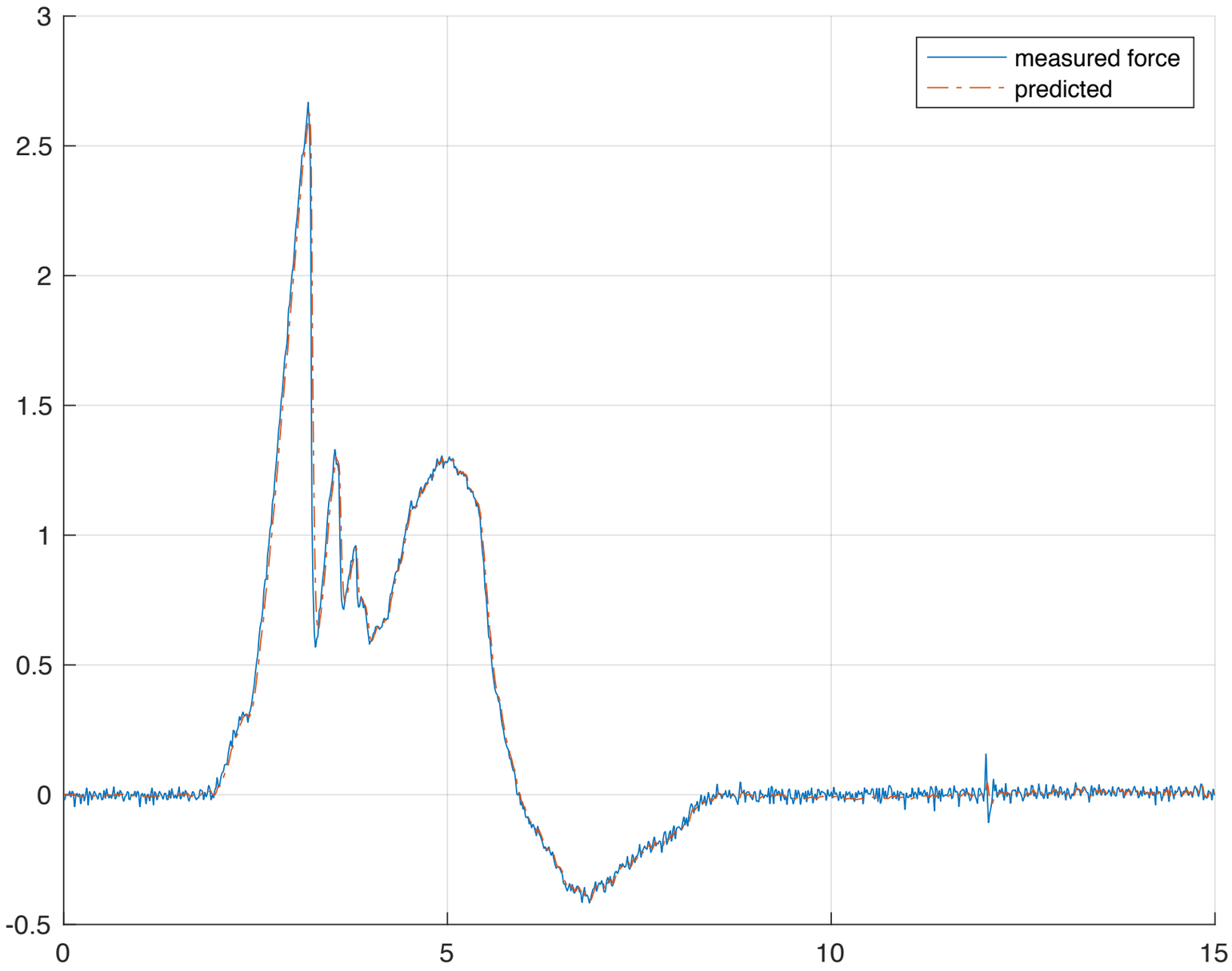
$$\gamma = \frac{\sigma_1^2 - \sigma_0^2}{2} \quad , \quad \nu = \frac{\sigma_1^2 + \sigma_0^2}{2}$$

**threshold** **drift**

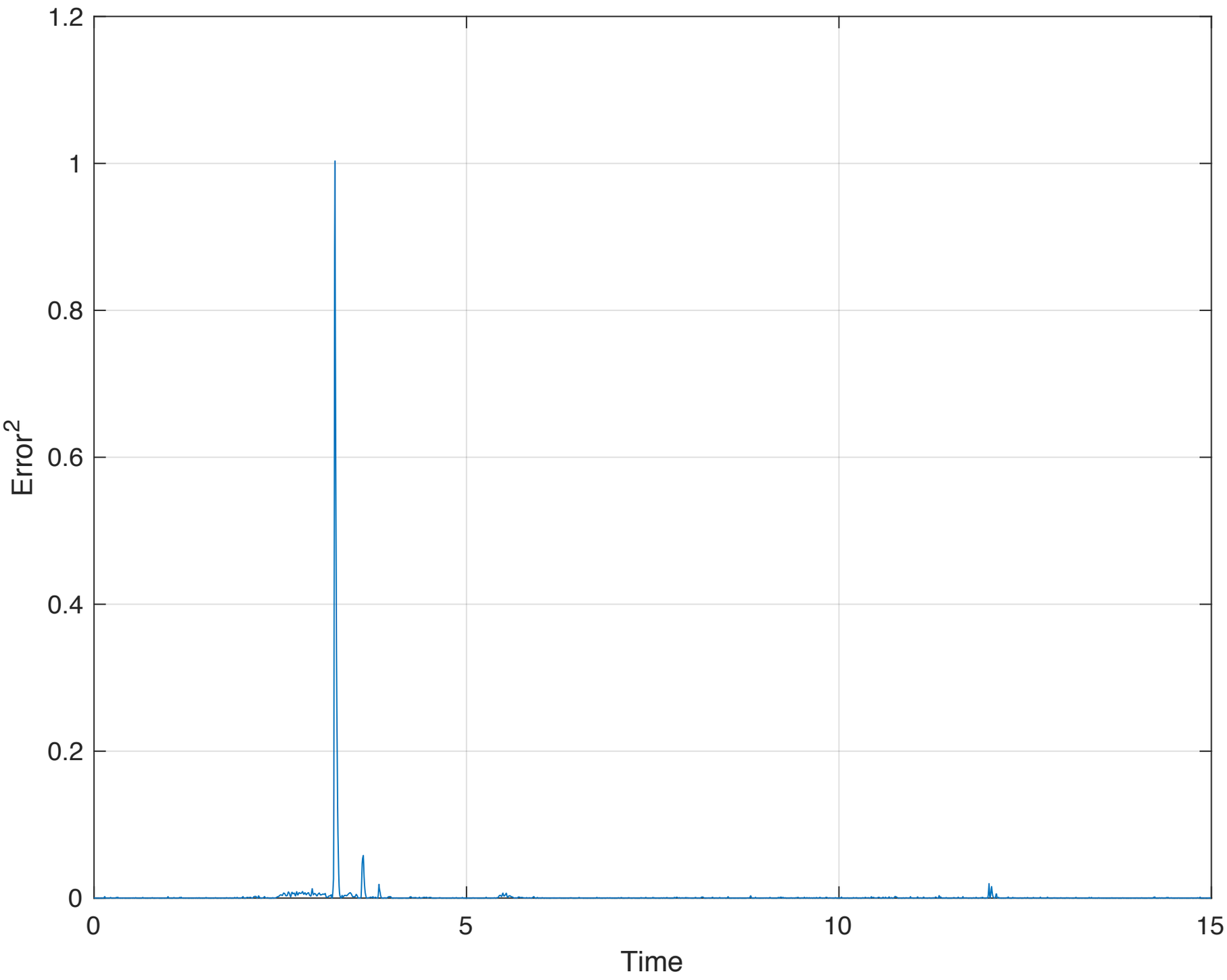
$\sigma_0^2 =$ variance of no-rupture case

$\sigma_1^2 =$ variance of abrupt change case

# Force prediction

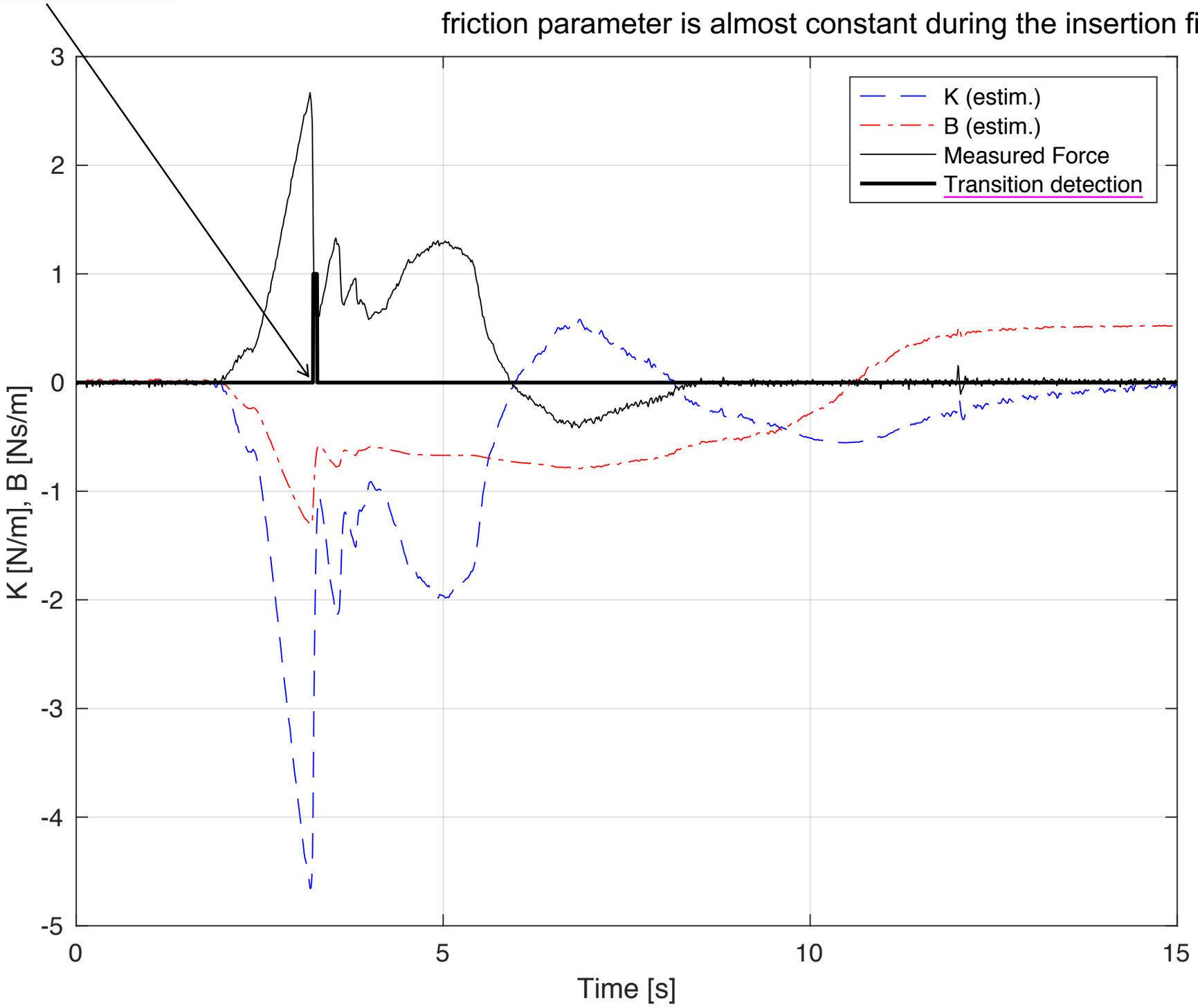


# Prediction error

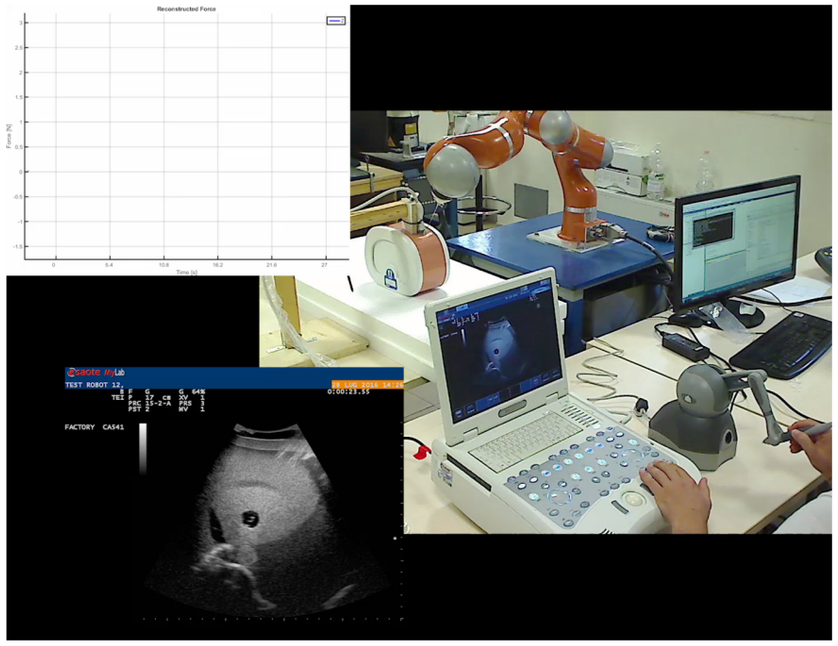


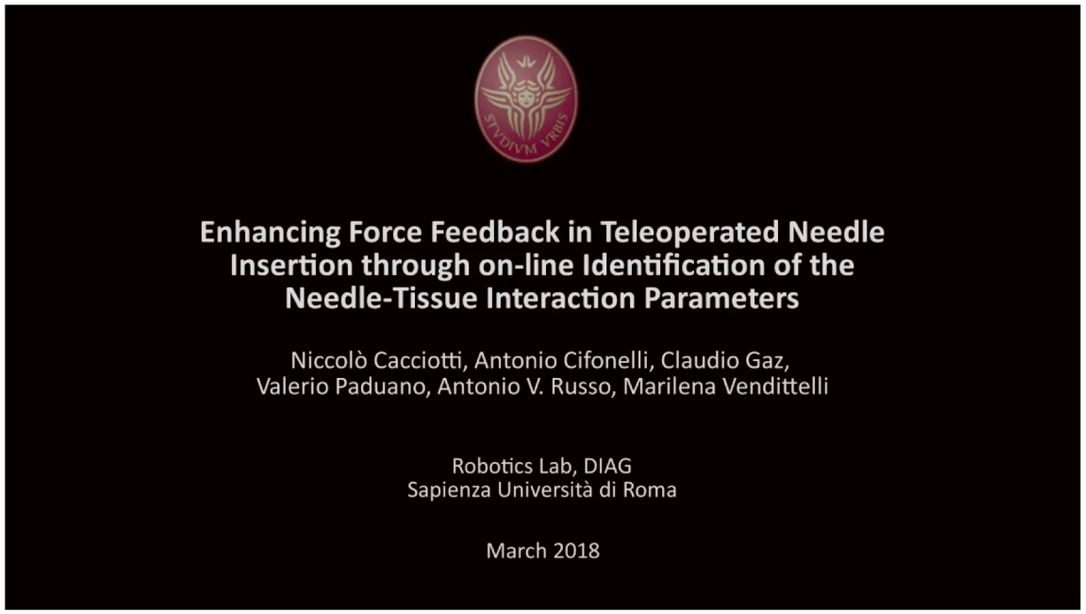
# Detection of layer transition

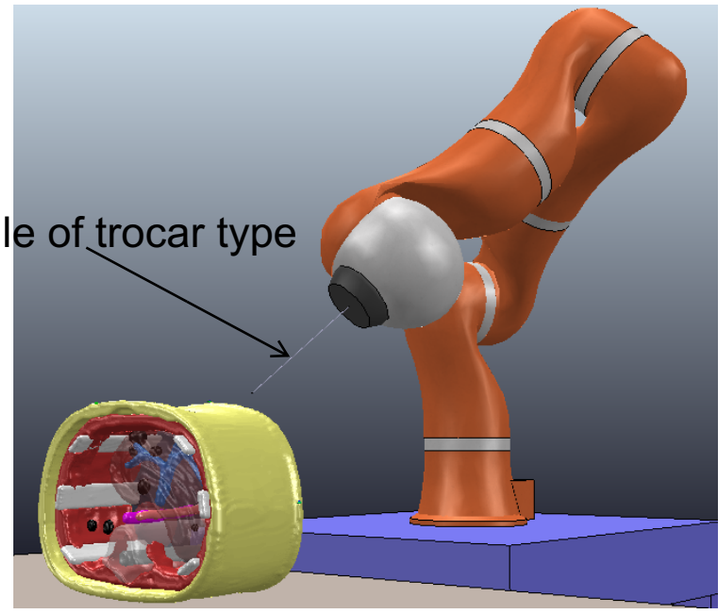
## (puncturing event)

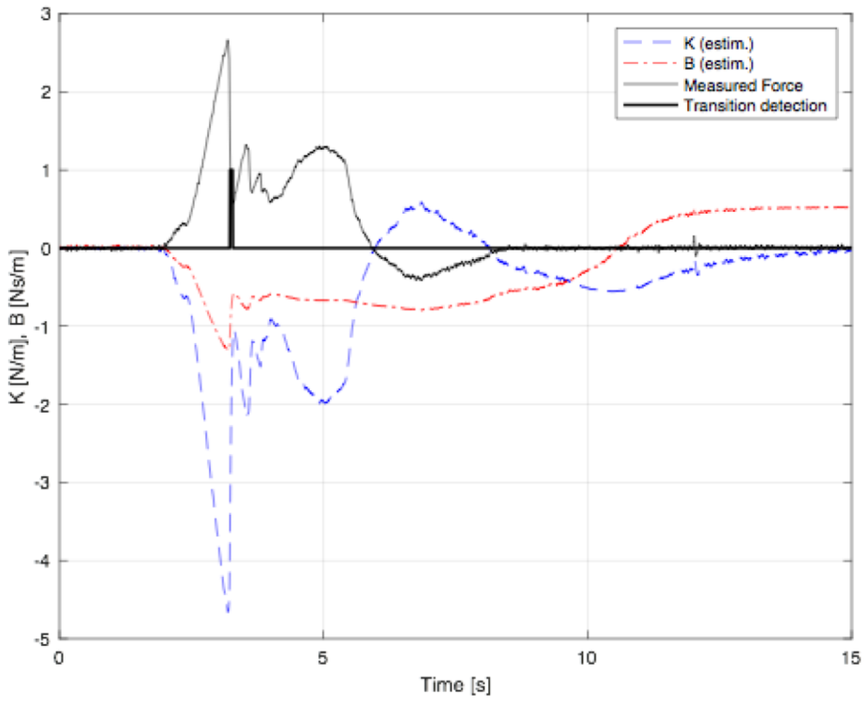


# experimental setup @Robotics Lab



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3. BARBÉ L., BAYLE B., DE MATHELIN M. GANGI A. (2007). In Vivo Model Estimation and Haptic Characterization of Needle Insertions. The International Journal of Robotics Research, 26, 1283–1301.
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