Biological Tissue Cutting Mechanics and Dynamics

Introduction

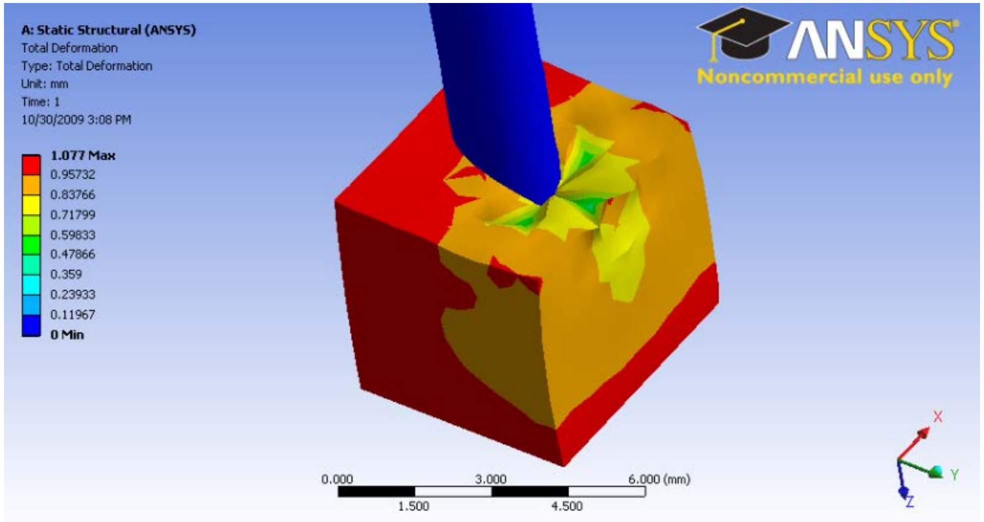
Research Objectives:

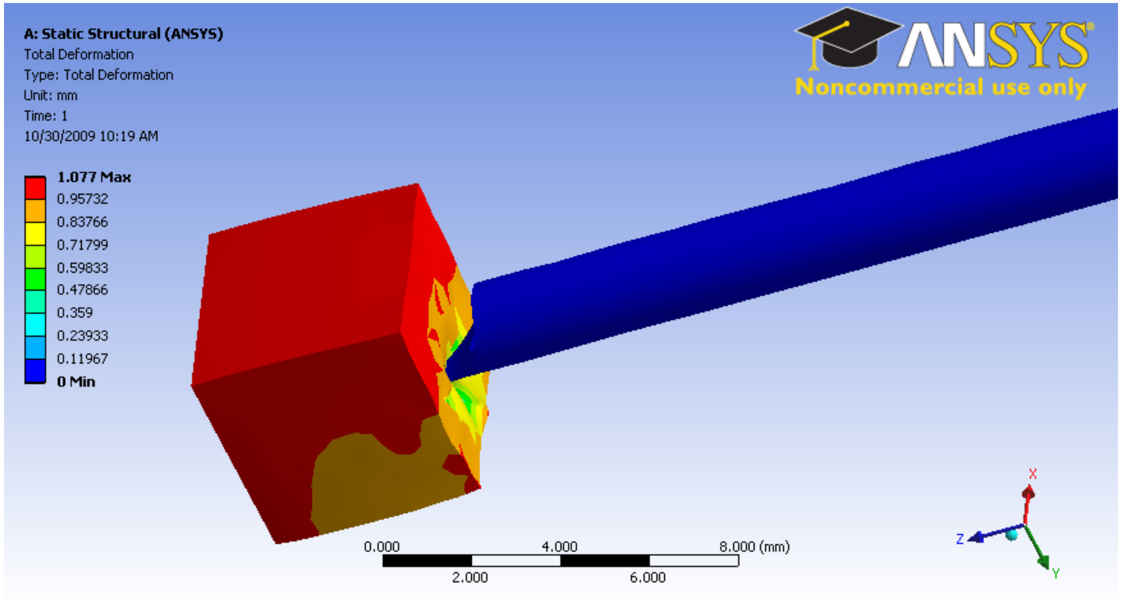
- Develop tissue cutting mechanics theoretical foundation to describe geometry and cutting forces of a needle, penetrating inside a tissue
- Develop an analytical model that describes geometry of a needle tip in terms of its characteristic angles
- Develop tissue cutting dynamics theoretical foundation to describe needle motion during its penetration inside a tissue

Approach:

- Use conventional metal cutting mechanics theory and represent the needle cutting edge as a distribution of infinitesimal cutting edges described by 4 characteristic angles: inclination, velocity, normal and effective rake angles.
- Combine the metal cutting mechanics approach and the fracture mechanics method to formulate the fracture force model for the needle active cutting edge
- Use a velocity controlled formulation of the equation of motion of a needle and combine it with the developed cutting mechanics model
- Experimentally verify the developed needle motion model

Needle/Tissue FEM model





Needle/Tissue Interaction Simulation (ANSYS 12 FEM)

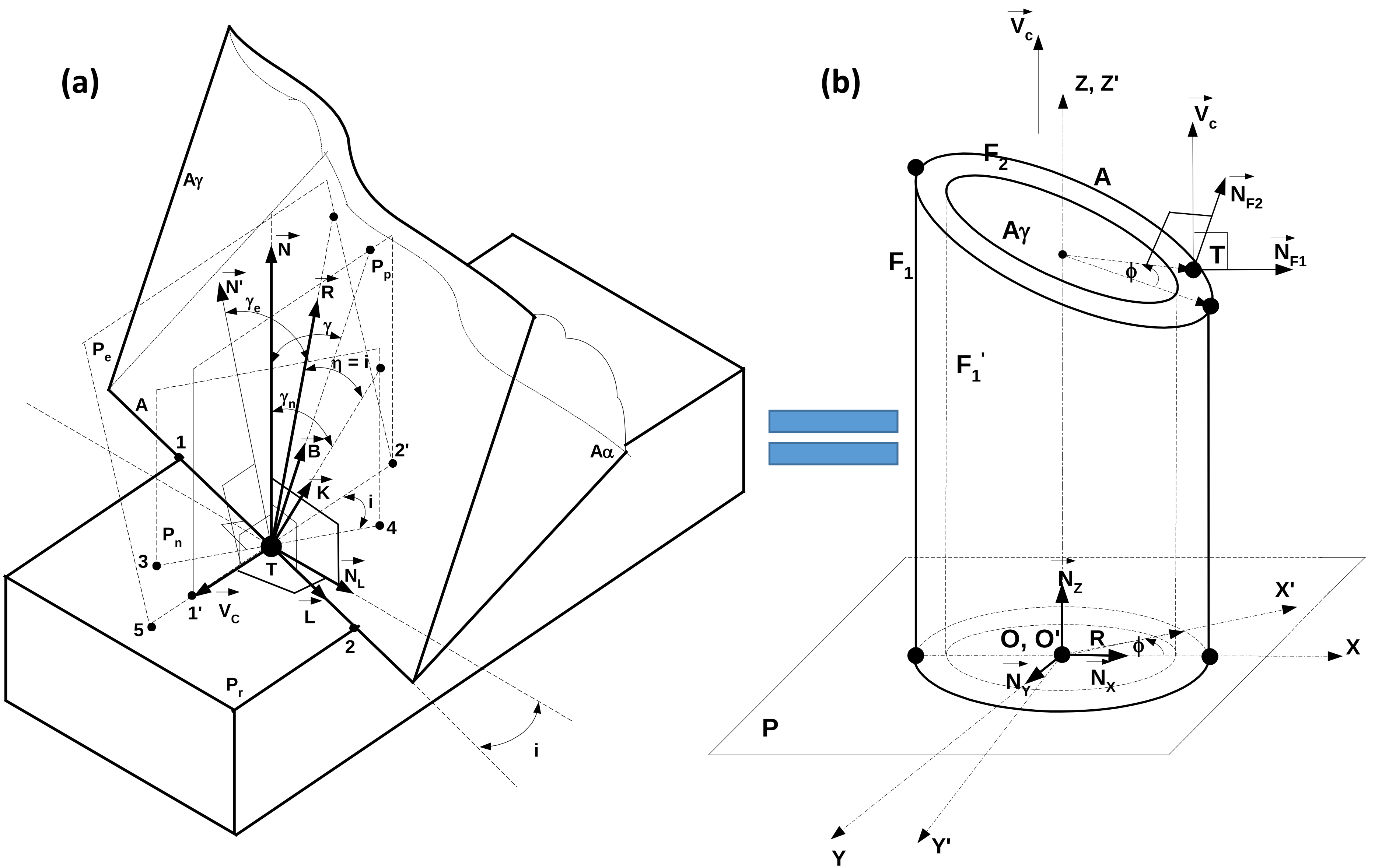
Applications and challenges

- **<u>Model Major Output:</u>** "force signature" (insertion force vs. insertion time)

- **<u>Model Applications</u>**: usage of the "force signature" to accelerate performance of the haptic loops of the virtual surgical simulators; as a validation tool of FEM models of tissue cutting processes (brachytherapy, biopsy, etc.); as a new theoretical basis for the tissue cutting mechanics; and others;

- **<u>Model Challenges</u>**: prediction of abnormal cutting force ("force signature") oscillations during the needle/tissue interaction process, such as: oscillations due to the variable tissue fracture toughness; oscillations due to the needle/tissue system dynamics effects (needle motion controller induced instability, etc.); oscillations due to the Poynting effect; oscillations due to the stick-slip friction; oscillations due to the tissue springback effect and others.

General Analytical Model for Any Rake and Inclination Angles

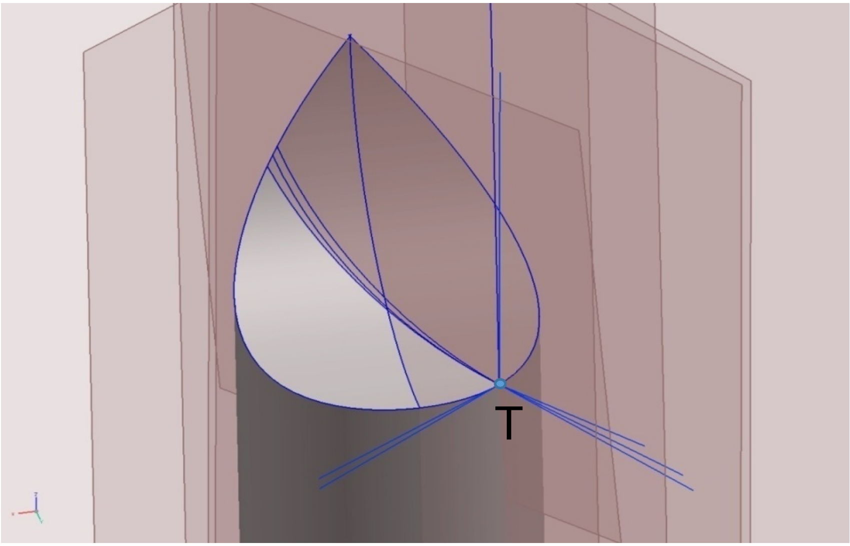


Oblique cutting model: (a) single-point cutting tool, (b) needle tip cutting edge

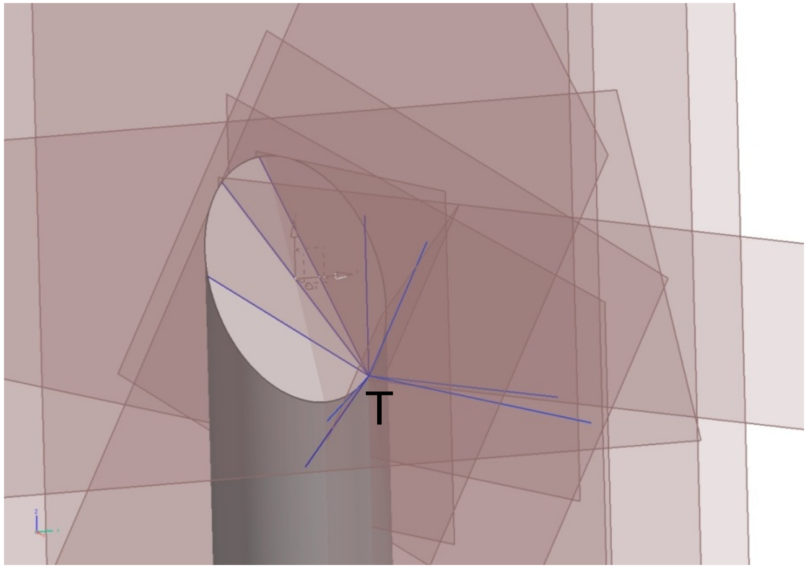
Given vectors: $\vec{N}_{F1}$ (cylindrical surface), $\vec{N}_{F2}$ (rake surface) , $\vec{N}_X$, $\vec{N}_Y$, $\vec{N}_Z$.

Needle Types

Cylindrical Tip Needle

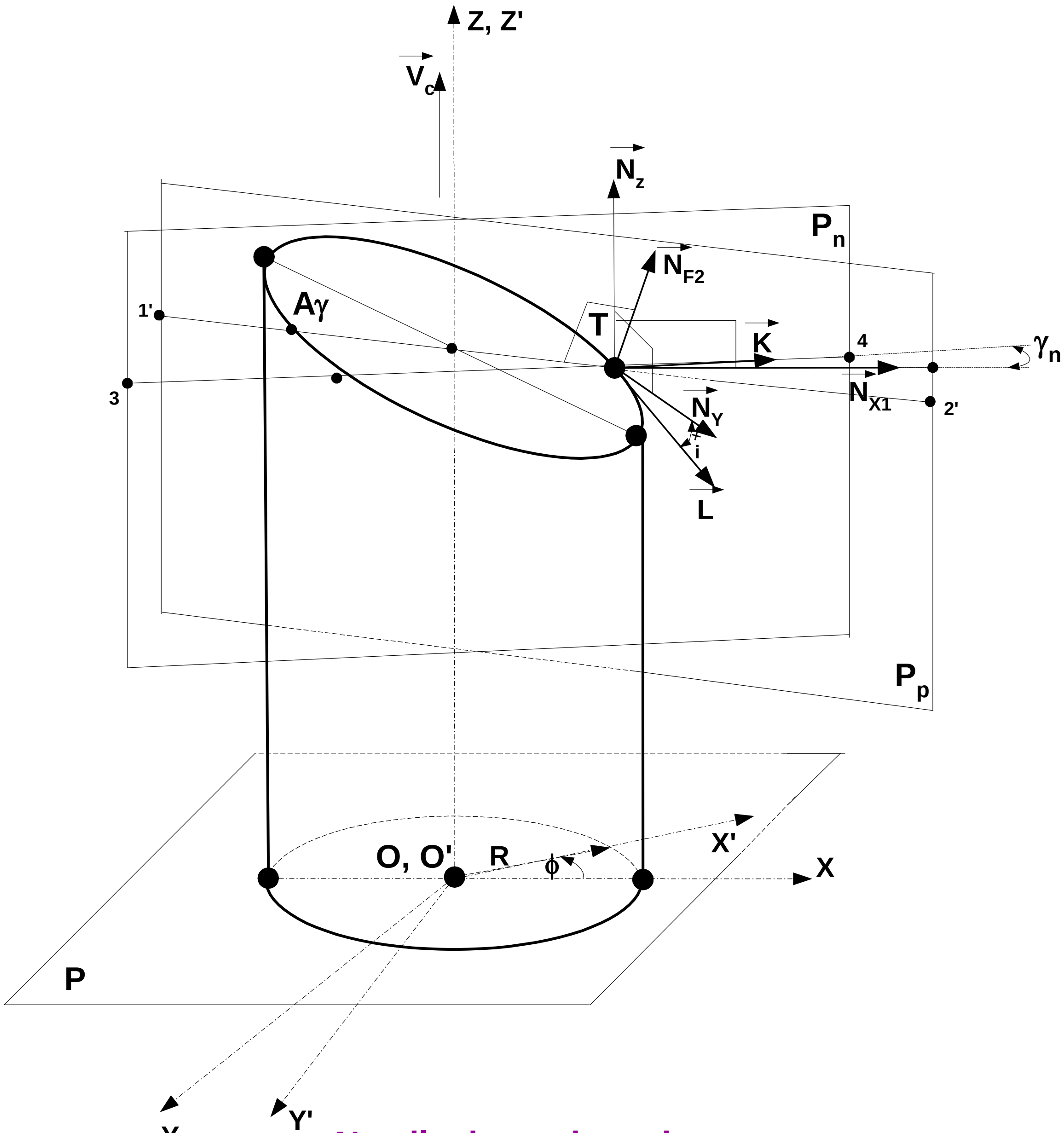


Bevel Tip Needle



Solid models of the needle tips and their characteristic angles (UNIGRAPHICS NX 6)

Analytical Model of a Normal Rake Angle Distribution

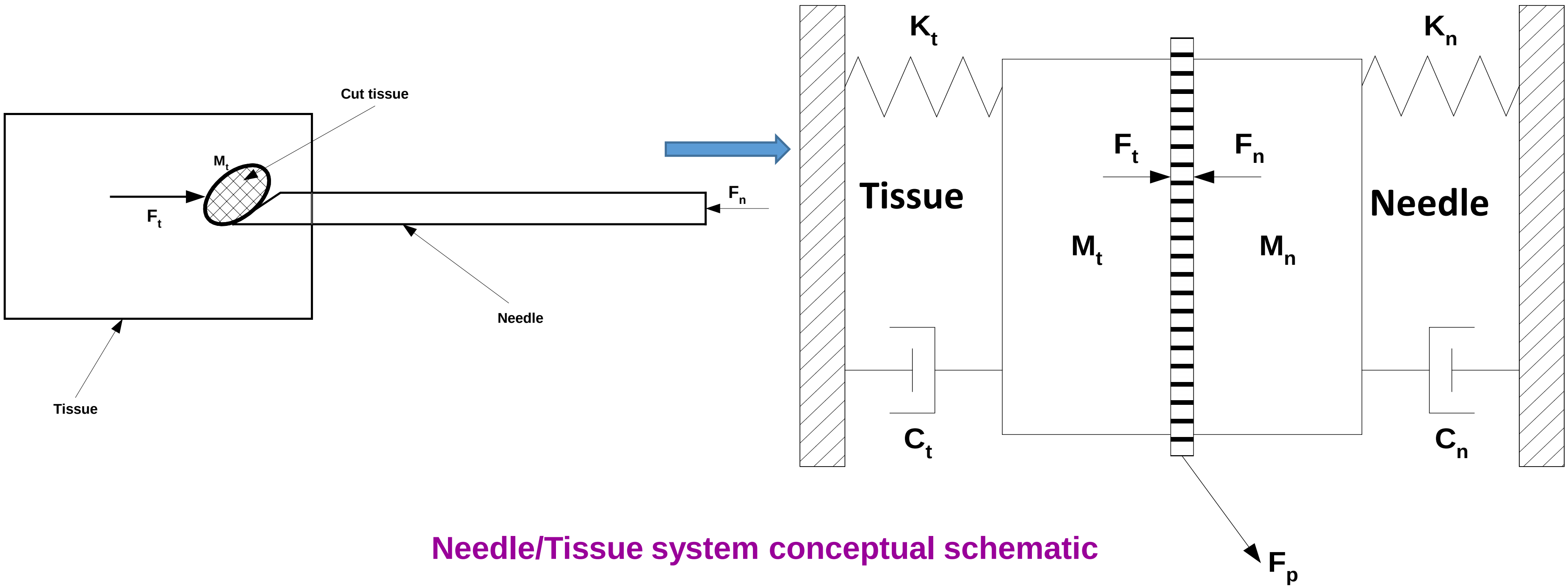


$$\gamma_n = a\tan\left(-\frac{\frac{\partial F_2}{\partial x}}{\sqrt{\left(\frac{\partial F_2}{\partial z}\right)^2 + \left(\frac{\partial F_2}{\partial y}\right)^2}}\right)$$

Normal rake angle model

Needle tip cutting edge

Cutting Dynamics



Needle/Tissue system conceptual schematic

$$F_{C\,ave} = -R\mu \cot\xi \cot\frac{\phi}{2}\,\Big|_0^{\psi} +$$

$$+\frac{R\mu}{\cot\xi}\left(4\tan\frac{\varphi}{2}\left(a+b\tan^2\frac{\varphi}{2}+c\tan^4\frac{\varphi}{2}\right)^{-1}\Bigg|_0^{\psi}-\frac{1}{5}\tan^3\frac{\varphi}{2}\left(a+b\tan^2\frac{\varphi}{2}+c\tan^4\frac{\varphi}{2}\right)^{-1}\Bigg|_0^{\psi}+2\frac{4}{5}\right)$$

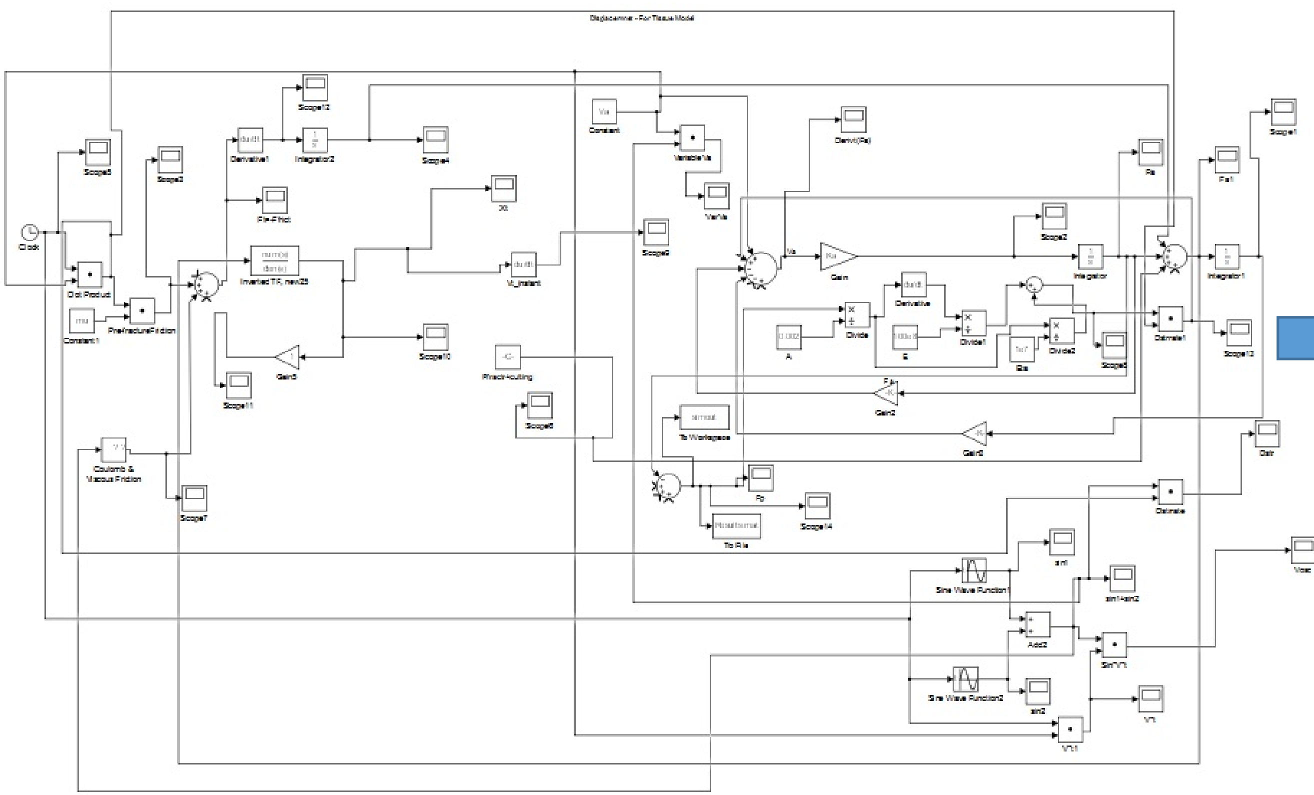
Fracture force of a bevel tip needle

Cutting Dynamics

Equations of motion of the needle/tissue:

$K_n^{-1}\dot{F}_n + C_n^{-1}F_n + M_n^{-1}\int F_n = V_n(t)$ **- needle** or $K_n^{-1}\dot{\sum} F_{n_i} + C_n^{-1}\sum F_{n_i} + M_n^{-1}\int \sum F_{n_i} = \sum V_{n_i}(t)$

$\frac{F_t(s)}{x_t(s)} = M_t s^2 + C_t s + K_t$ **- tissue**

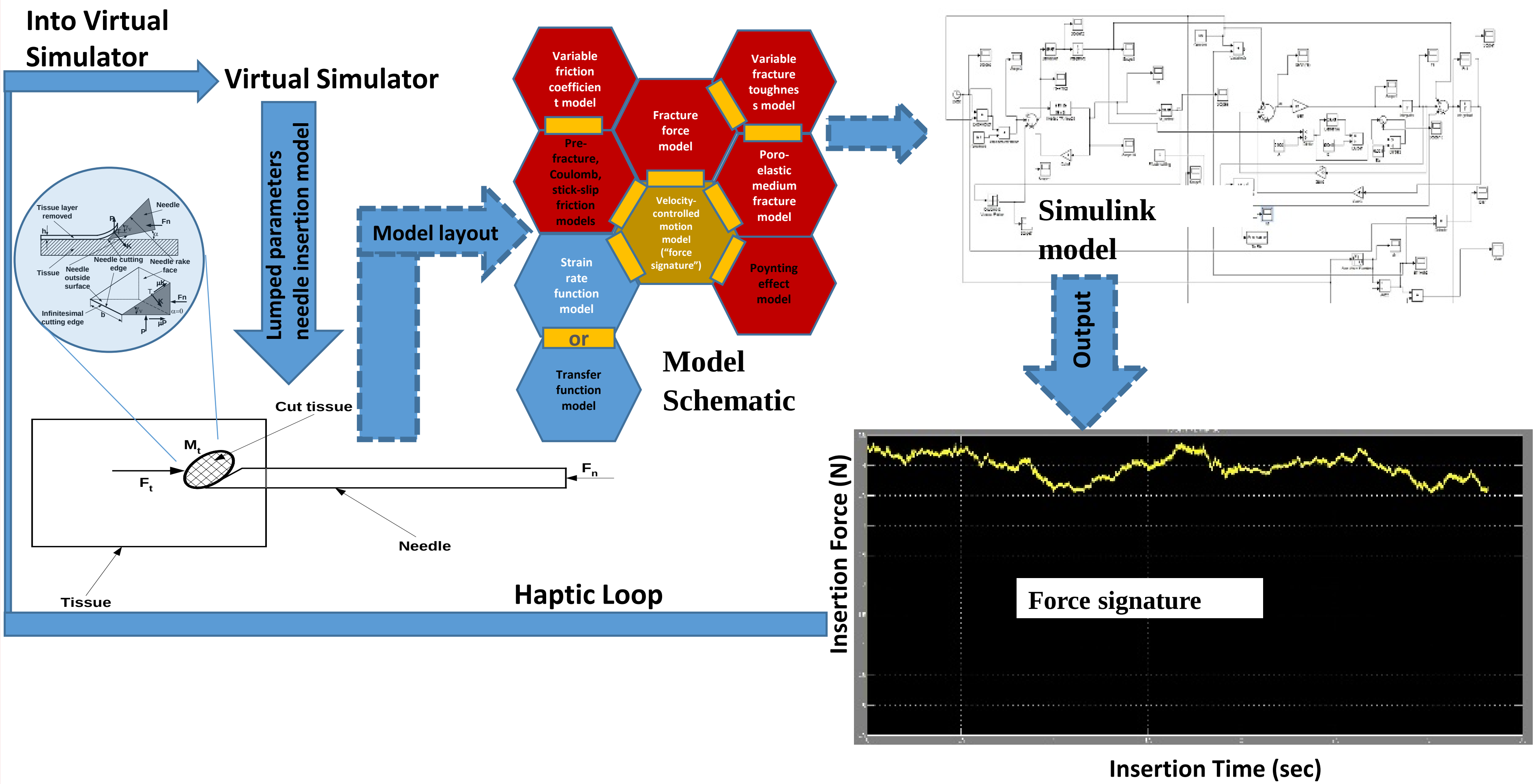


Output

"force signature"

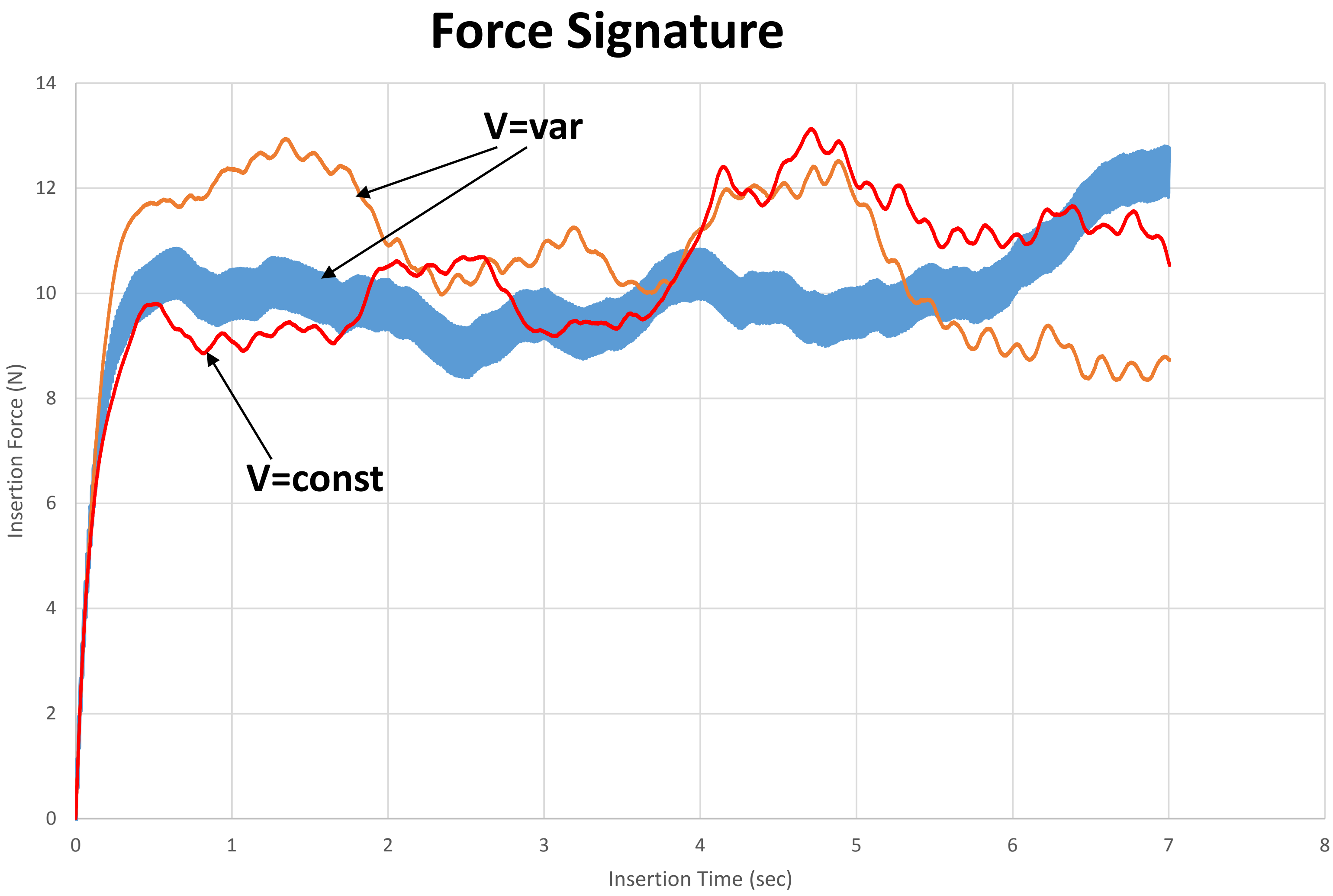
Simulink/Matlab needle/tissue interaction model

Mechanics and Dynamics of Needle Insertion Into Tissue Simulation Example



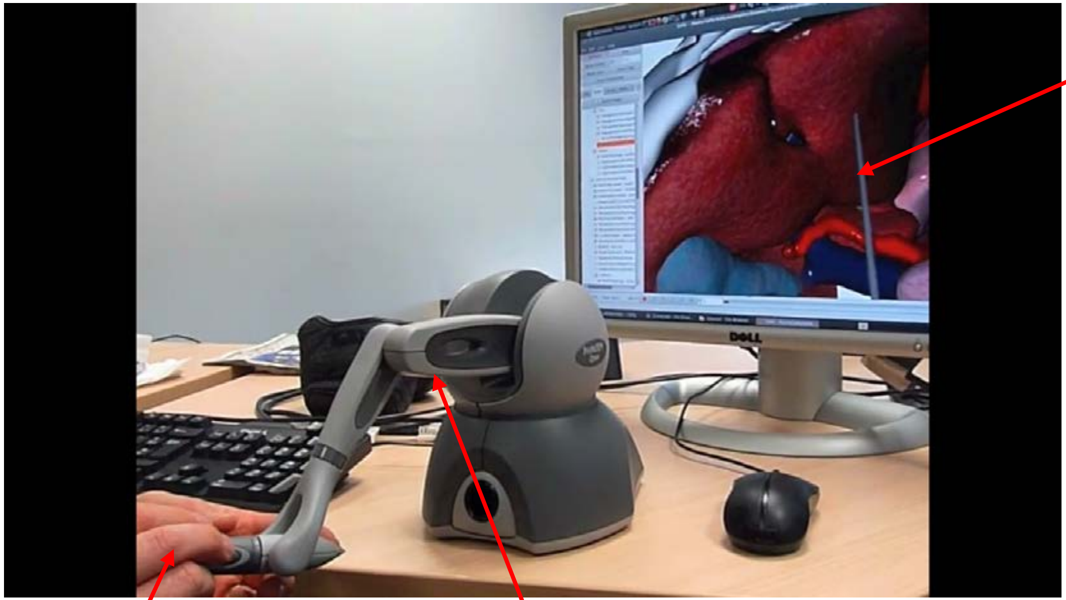
Simulink/Matlab needle/tissue interaction model as a part of a haptics loop of a virtual surgical simulator

Mechanics and Dynamics of Needle Insertion Into Tissue Simulation Example



Simulink/Matlab results of needle/tissue interaction model: needle insertion velocity (V) controlled solutions

Example of the Model Application



a “force signature” can be used in order to accelerate the haptics loop of a virtual surgical simulator”

Haptics Loop of a Virtual Surgical Simulator (curtesy of Dr. Hadrien Courtecuisse, INRIA, France)

Thank you!