Suturing Simulation Based on Complementarity Constraints

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Background

The field of medical simulation has seen many contributions concerning the area of soft tissue modeling.
Suture is a complex tast in surgery and its simulation involves needle driving and thread-tissue interaction.
Most of the existing interaction models for suture are simplified, often need remeshing and don't necessarily rely on physical laws.

We propose a new method based on complementarity constraints capable of simulating all the key aspects of a suturing task.

Overview of our method

Deformation models:

We use a finite element model of serially-linked elements based on beam theory for the deformation of the needle and the suture.
The soft tissue relies on a volumetric finite element method that can handle geometrically non-linear deformations.

No remeshing:

Constraints can be created anywhere, the forces applied on the embedded points being converted to equivalent forces applied on the vertices.

Interaction model:

We use complementarity constraints to model all the interactions of a suturing task:

- **Contact** between objects, autocollision of the suture thread.
- **Puncturing** of the needle tip when a threshold force is reached.
- **Cutting** of the needle tip and the resistance from the tissue.
- **Friction** for the contacts and for the suture inside the tissue.
- **Path** constraints sampled regurlarly ensure that the thread stay on the curve created by the needle.

Resolution:

We use a Gauss-Seidel like algorithm to solve the system of constraints.
Compliance warping enables us to compute a fast approximation of the compliance matrix.

References

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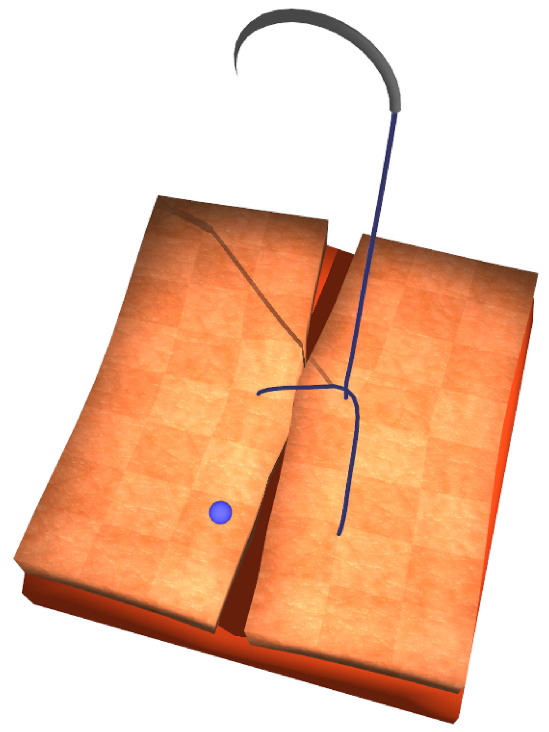
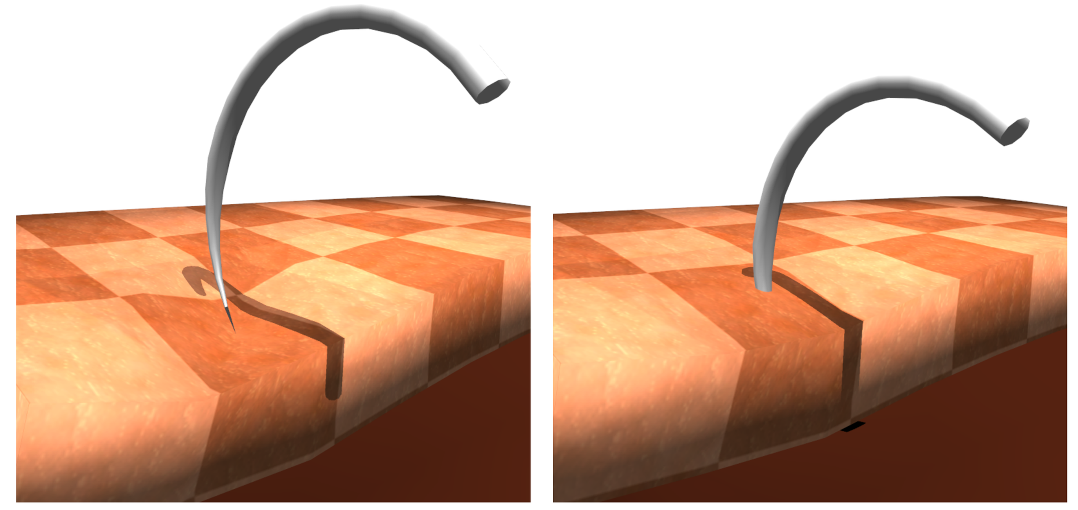
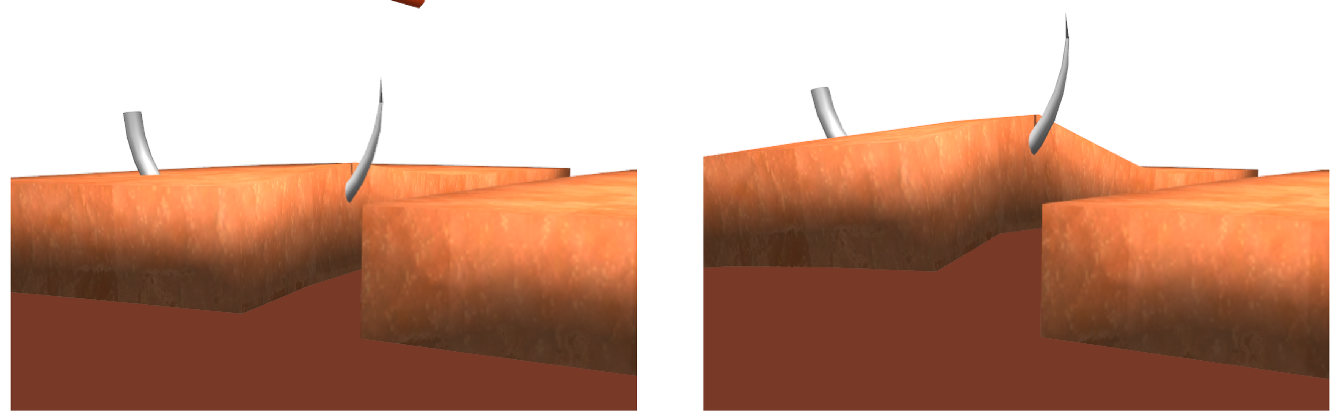
Constraints



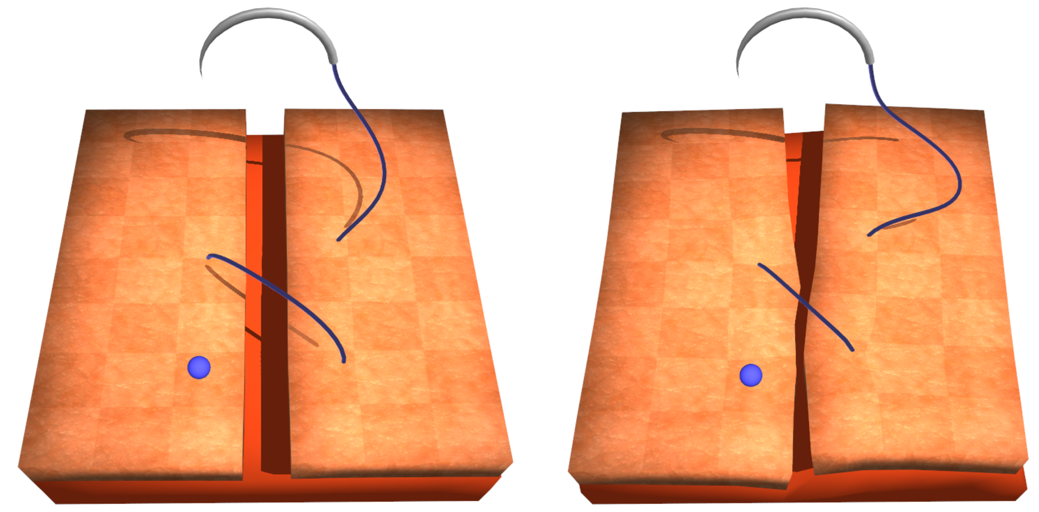
Unilateral constraints are created by the collision detection algorithm to model contacts: contact between the soft tissue walls, between the tissue and the needle or the thread and autocollision of the suture thread.
We model dry friction during contact using the Coulomb's friction law.



Contact between the needle tip and the tissue is modeled differently: if the interaction force reaches a puncturing force threshold, the needle starts penetrating the soft tissue.

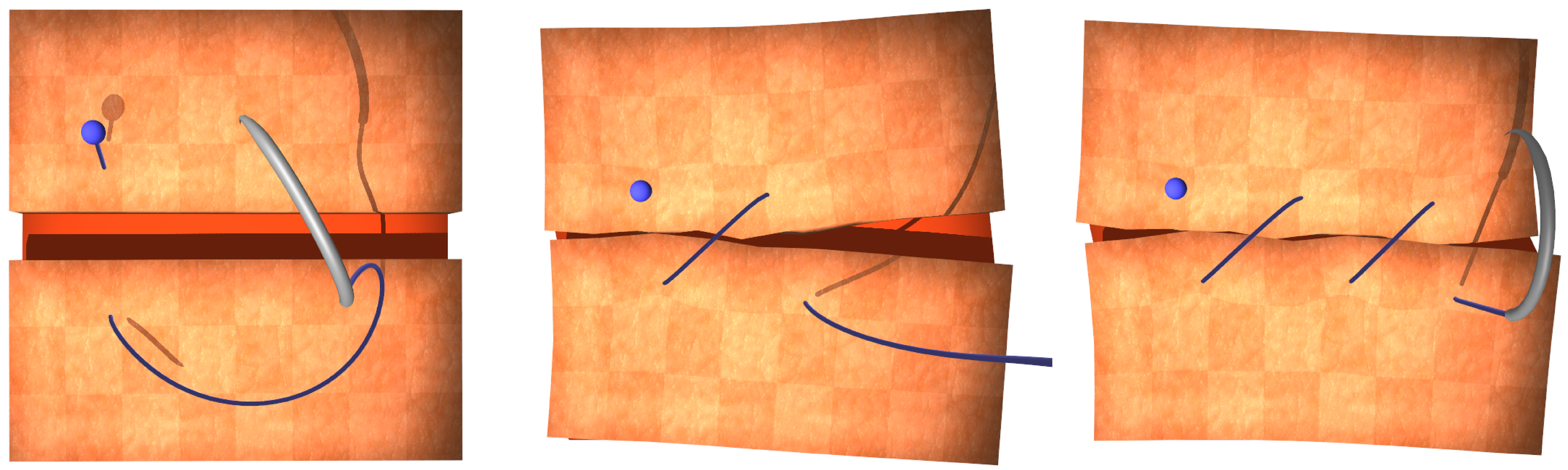


We create bilateral constraints on the curve created by the needle tip to ensure that the needle shaft and the thread stay in that path.
Constraints are sampled regularly within the soft tissue and are static relatively to the motion of the surrounding tissue elements.
Figure: the tissue deformation follows the needle motion when it is moved up.



When moving inside the tissue, the needle and surgical thread are slowed down by friction due to the tissue. A Karnopp friction model is used.
Figure: tightening a suture and releasing the thread, without friction and then with friction.

Results



Exemple of a simple suturing task. The tissue is structured in two layers, stiff on top and softer on the bottom. The top layer representing the skin is separated in two halves and the objective is to perform a suture which will join the two parts.
We show that several virtual suture points can be simulated and that we can pull on the thread for tightening the suture while capturing and solving the contacts between the parts of the skin layer.
The needle and the thread are modeled by 100 beam elements and the soft tissue by 300 hexaedrons. The simulation runs over 25 fps on a Core2Duo 2.66GHz with 2GB RAM.

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