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Suturing simulation based on complementarity constraints

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Abstract

This paper introduces a new method, based on complementarity constraints, for simulating virtual sutures in soft tissues. Complementarity constraints are known for the modeling of contacts with friction between solid objects, however they can be used for other types of interactions. We focus on modeling the physical nature of the interactions between a soft anatomical structure and a needle or surgical thread during a suturing task. In particular we model needle puncture through soft tissues, followed by the friction that occurs when sliding through the tissue, the cutting forces associated to different tissue layers, and the collision with boundary membranes. A common iterative solver is used for all constraints, in combination with an implicit integration scheme, providing fast and stable simulations even for complex scenarios.

1. Introduction

In this paper, we introduce a new *generic* method for simulating the interaction of thin (and flexible) medical devices with soft tissues. The proposed approach is able to handle all key steps of a suturing simulation, i.e. needle driving, soft tissue deformation, thread interaction with the tissue. Consequently the method is almost independent of the choice of the soft tissue, needle or thread models. We use a unique model for both describing the (rigid or flexible) needle and the surgical thread. For this we rely on a finite element model of serially-linked beam elements, as introduced by Cotin *et al.* in [CDL*05] for the simulation of a catheter. The soft tissue model relies on a volumetric finite element method that can handle geometrically non-linear deformations.

2. Constraint-based interaction model

Our main contribution is a new interaction model to describe the mechanical phenomena occuring during suturing tasks. We rely on complementarity theory to describe the interactions between the needle or surgical thread and the soft tissue.

We note δ the measure of a distance between a current state and the wanted target state of the constraint. λ represents the force used to solve the constraint. We suppose that the mechanical model of the interacting objects could provide a linearized law between them:

$$\delta(\lambda) = \mathbf{W}\lambda + \delta_0 \tag{1}$$

where $\mathbf{W}$ is a compliance measure and δ_0 the value of δ when λ vanishes to zero. This law is called the *compliance law*. Each constraint defines another law between δ and λ, called the *constraint law*. As we know the two laws, the unknown values of λ and δ can be generally computed easily. However, all constraints are coupled and the δ_0 value depends on other constraints and asks for an iterative approach during the global solving process.

In order to present the constraints used in our method and their *constraint law*, we suppose that δ_0 is known. For the simulation of a suture task, we combine five constraints:

- **Contact** constraints prevent objects from interpenetration. δ_c is then a measure of interpenetration depth between two objects in contact. Contacts are inherently unilateral constraints and commonly modeled with complementarity constraints. We consider dry friction during contact, using the well known Coulomb's friction law.
- **Puncture** constraints are used to model the interaction between the needle tip and the tissue. It is similar to the contact constraint: it tries first to prevent the interpenetration. However, when the interaction force λ reaches a puncturing force threshold f_p, the needle starts penetrating through the soft tissue. In this case, we impose a null relative displacement δ_n between the needle and the organ along the directions normal to the needle shaft.
- **Cutting**. As the needle penetrates through the tissue, it encounters a certain resistance from the material slowing down its motion. For the needle to cut though the tissue and move forward, the force applied to the needle needs to overcome this cutting force f_c.
- **Path**. During the navigation of the needle and thread through soft tissues, we use bilateral constraints to ensure that the needle shaft and the suture thread stay in the path

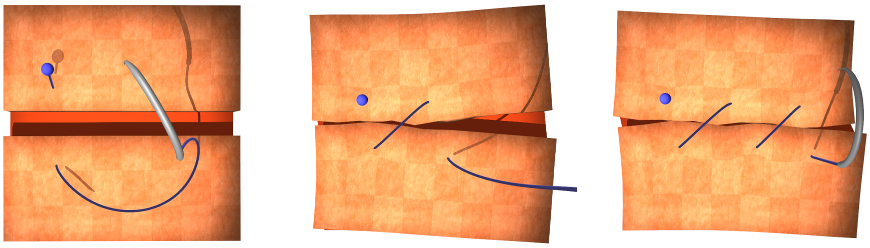

Figure 1: *Basic suturing skills simulation : three suture points are created and tightened to close a wound.*

created by the needle tip. This is achieved by imposing a null relative displacement $\delta = 0$ along the directions normal to the needle-thread curve. Constraints are sampled regularly along the path of the needle-thread curve, are created within the mesh describing the soft tissue and are static relatively to the motion of the surrounding tissue elements.

- **Friction**. When moving inside the tissue, the needle and surgical thread are slowed down by friction due to the pressure exerted by the tissue onto the thread. We integrate the friction along the insertion path, and the friction resistance is given by the Coulomb's model of friction, with an additional damping coefficient.

Applying constraints on arbitrary points within a volume or surface mesh is critical, as it removes the reliance on dynamically remeshing often required by other methods. First, we need to be able to update the point position given new positions of the mesh vertices. Then, forces applied by the constraint solver to the embedded point must be converted to equivalent forces applied to the vertices. Observing the virtual work principle, this can be done with a projection, as explained in [NKJF09] for penalty forces.

To solve the system of constraints described above, we use a Gauss-Seidel-like algorithm modified so that it uses the behaviour law defined by each constraint, similar to [GDG08].

3. Results and future work

We illustrate our results on a suturing task where the soft tissue is structured in two layers (stiff on top, softer on the bottom) as illustrated in Fig. 1. The top layer (representing the skin for instance) is separated in two halves, and the objective is to perform a suture which will join the two parts of the skin. This simulation involves a number of different types of constraints, and illustrates the flexibility and efficiency of our approach. We show that several virtual suture points can be simulated, that we can pull on the thread for tightening the suture while capturing and solving the contact between the parts of the skin layer. We also handle self-collision for the thread and contacts that occur between the thread and the soft tissue surface. Additionally we show that by computing dry friction between the thread and the soft-tissue we can simulate the fact that the suture holds when the thread is released.

For this study we used a FEM co-rotational approach with hexahedral elements to account for geometrical non-linearities in the deformation. As computing the compliance matrix for non-linear models can be prohibitive, we use an approach proposed by Saupin *et al.*, in [SDCG08] which shows how to compute a fast approximation of the compliance matrix for corotational models. One key point to obtain good result with our method is to use an implicit integration scheme. Indeed, simulation of the suture involves a strong concentration of constraints that are linked together by stiff mechanics. For this work, we use a backward Euler scheme.

Table 3 presents measures of performance of our method, obtained by timing key steps of the algorithm. The simulation was performed on a Core2 Duo 2.66GHz with 2GB RAM. The needle and the thread are modeled by 100 beam elements and the soft tissue by 300 hexaedrons.

Free Motion	10.30
Collision	2.97
Compliance update	23.39
Gauss-Seidel	2.14
Corrective motion	2.30
TOTAL	41.10
(FPS)	24.33

Table 1: *Average timings (ms) recorded for the simulation.*

We currently simulate all steps of a suturing task except knot tying. In the near future we plan to introduce an adaptive discretization of the beam elements, based on curvature, so that knot tying and other interactions can be described precisely without requiring too many elements. With some improvements in our computation times we could provide haptic feedback to the user.

References

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