A 2D Surgical Simulation Framework for Tool-Tissue Interaction

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Introduction

Challenges of surgical simulation for autonomy

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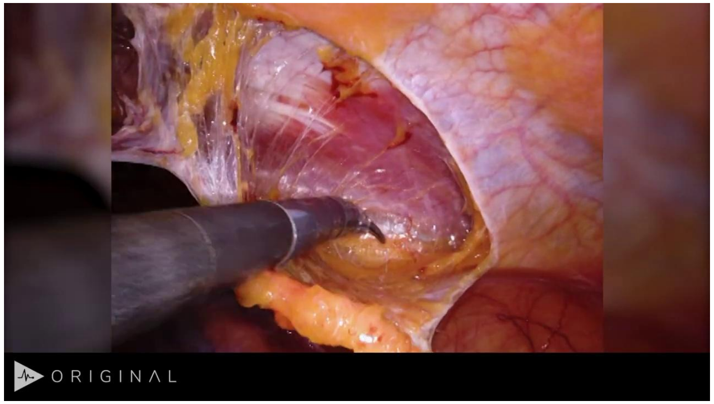

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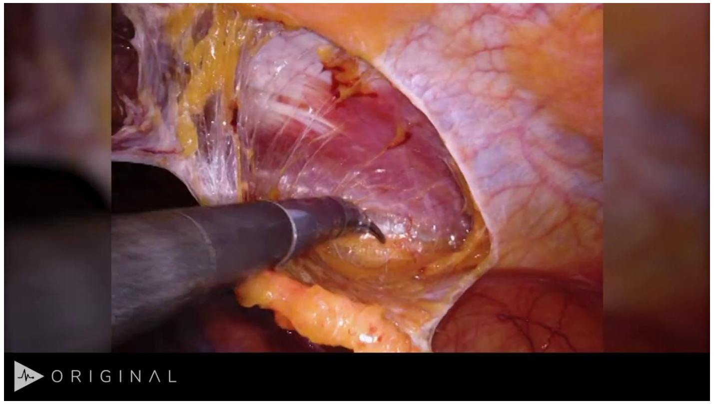

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Simulation

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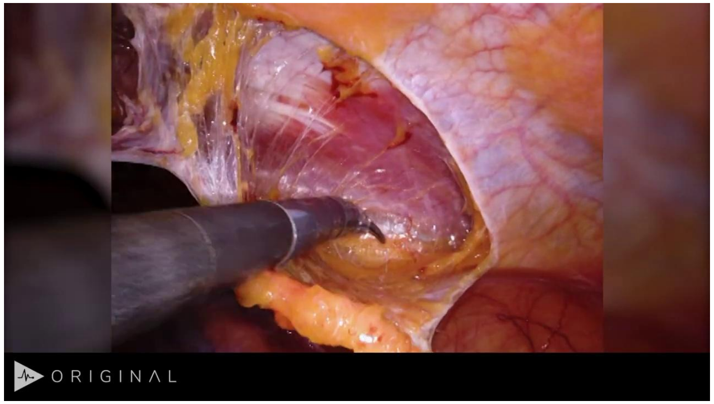

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Simulation

- Physical Modeling

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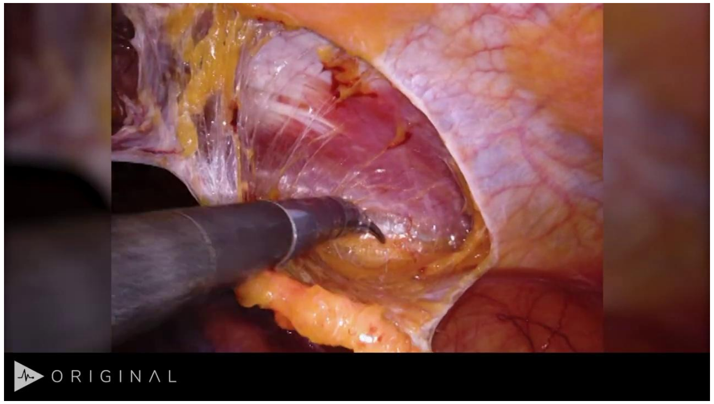

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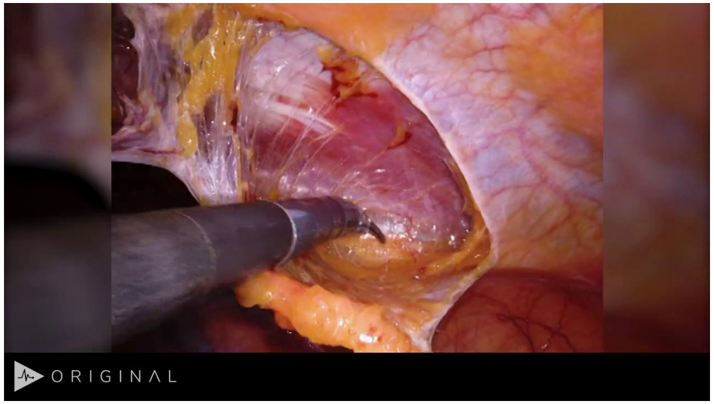

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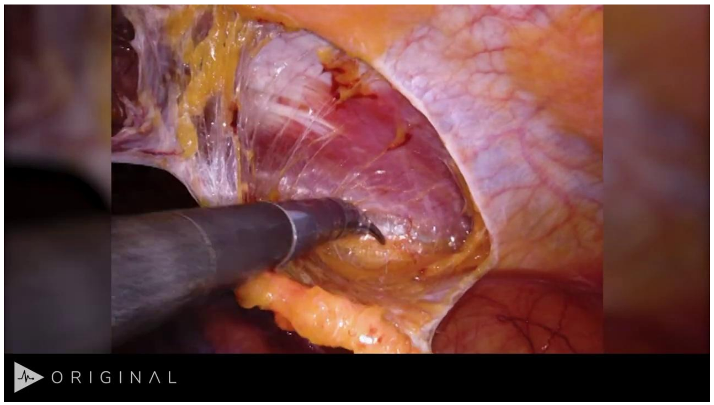

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Goals :

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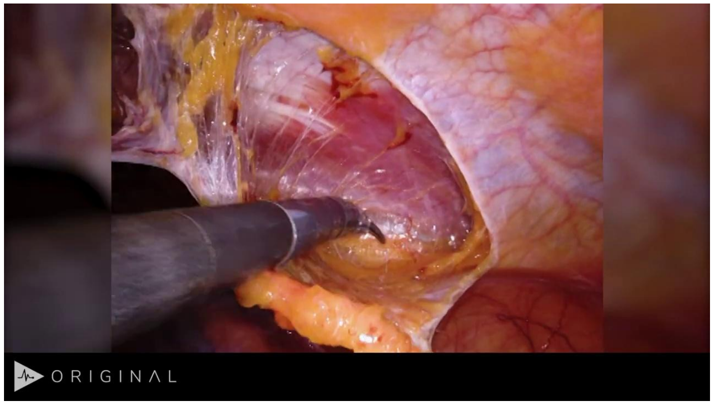

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Goals :

- tool tracking

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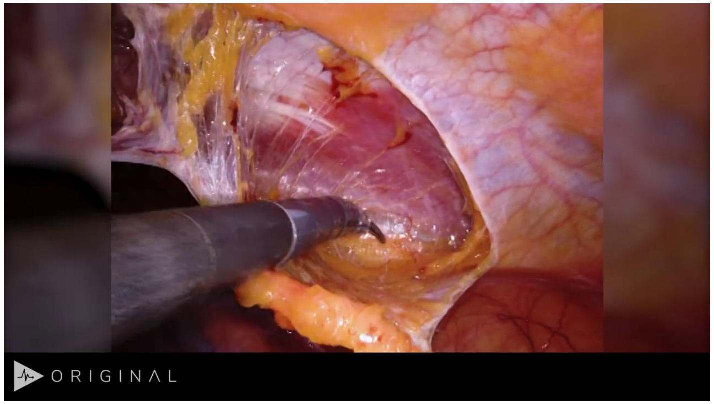

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Goals :

- tool tracking
- deal with tool-tissue interaction

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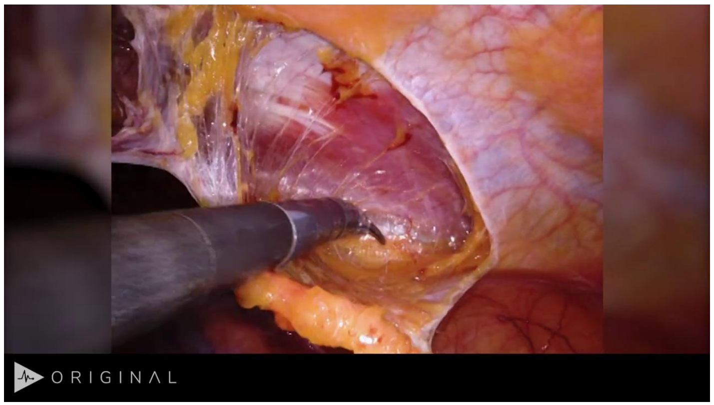

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- fast, real-time

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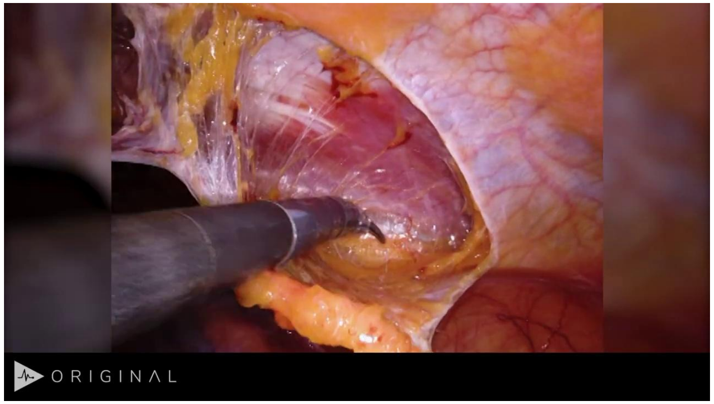

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- Visual Reconstruction
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Goals :

- tool tracking
- deal with tool-tissue interaction
- fast, real-time
- can be embedded into closed-loop control

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Contribution of our work

A novel 2D simulation framework includes four modules:

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Contribution of our work

A novel 2D simulation framework includes four modules:

1. Mesh generation using 2D tissue images
2. Position-based dynamics methods for tissue simulation
3. Collision detection method for tool-tissue interaction
4. Implicit Euler energy computation

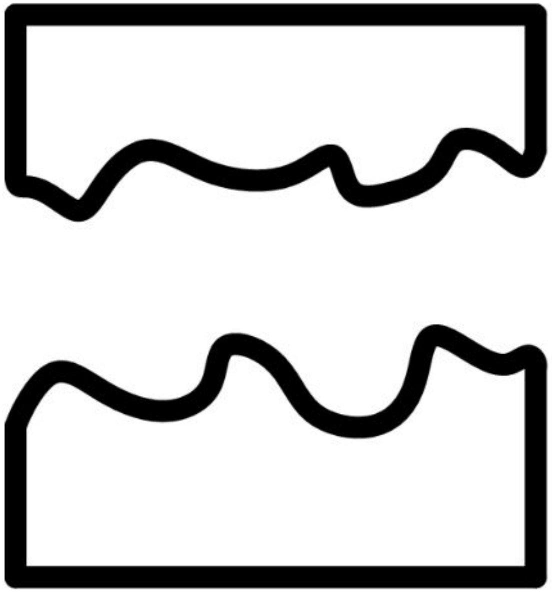
Methodology

Mesh Generation

Methodology

Mesh Generation

Image



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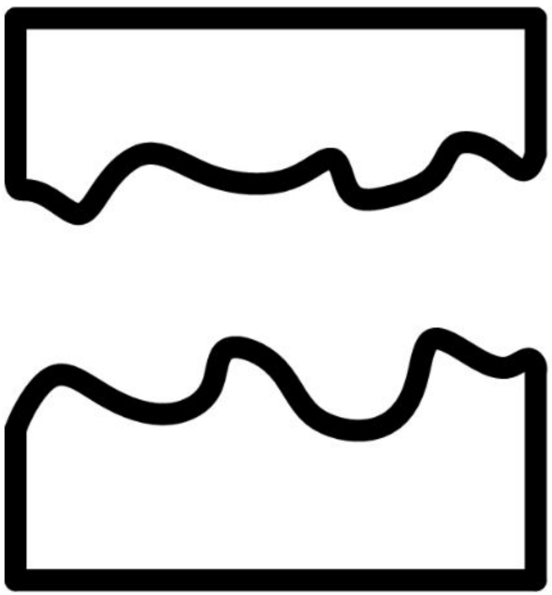

Contour points detection

Methodology

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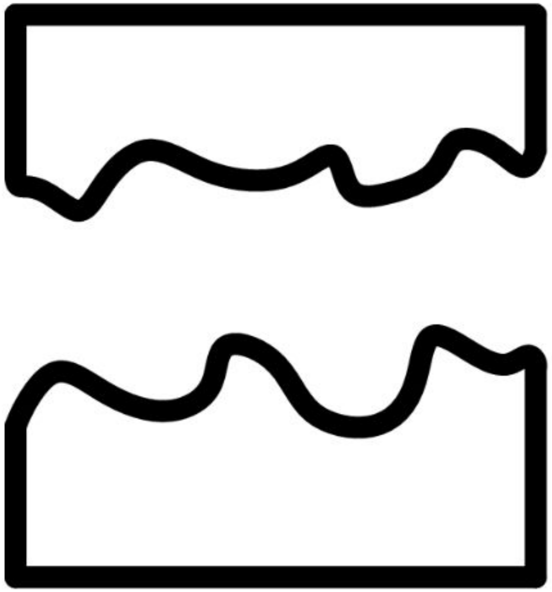

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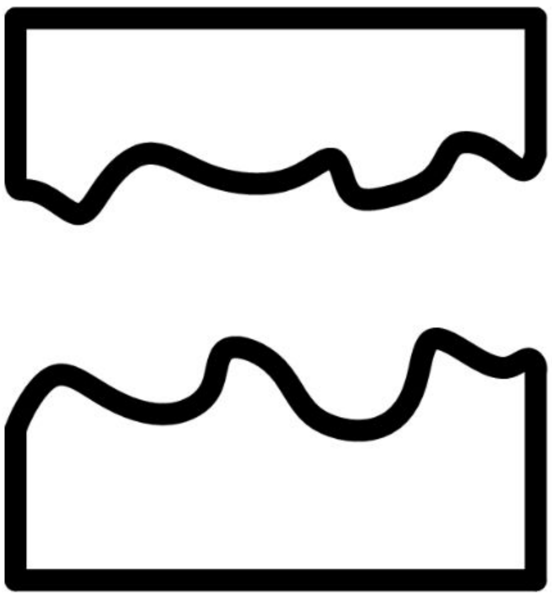

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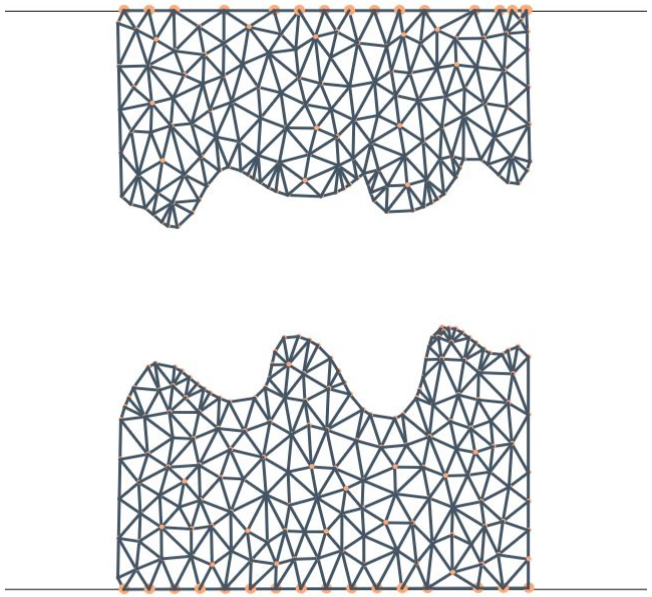

Methodology

Algorithm: Simulation Process (Position-based dynamics Simulation) [1]

[1] J. Bender, M. Müller, and M. Macklin, "Position-based simulation methods in computer graphics," in EUROGRAPHICS 2017 Tutorials. Eurographics Association, 2017.

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Algorithm: Simulation Process (Position-based dynamics Simulation) [1]

$$\mathbf{x}^* = \mathbf{x}^t + \Delta t \mathbf{v}^t + \Delta t^2 \mathbf{M}^{-1} \mathbf{f}_{ext}(\mathbf{x}^{\mathbf{t}})$$ ▷ **prediction step**

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While *iter < SolverIterations* **do**

  for *constraint C* $\in$ *M* **do**

    Compute $\Delta \mathbf{x}$ ▷ **constraint solving step**

    $\mathbf{x} = \mathbf{x}^{*} + \Delta \mathbf{x}$

  end

end

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end

$$\mathbf{x}^{t+1} = \mathbf{x}$$ ▷ **update position**

$$\mathbf{v}^{t+1} = \left(\mathbf{x}^{t+1} - \mathbf{x}^t\right) / \Delta t$$ ▷ **update velocity**

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Position-based dynamics Simulation

Solver: The position correction ΔX in each iteration can be computed on based on the constraint violation and its derivatives through Gauss-Siedel Method.

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- Distance constraint:

$$C_{\text{spring}}(\mathbf{x}_1, \mathbf{x}_2) = |\mathbf{x}_1 - \mathbf{x}_2| - d_0$$

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- Distance constraint:

$$C_{\text{spring}}\left(\mathbf{x}_1, \mathbf{x}_2\right) = \left|\mathbf{x}_1 - \mathbf{x}_2\right| - d_0$$

- Area conservation:

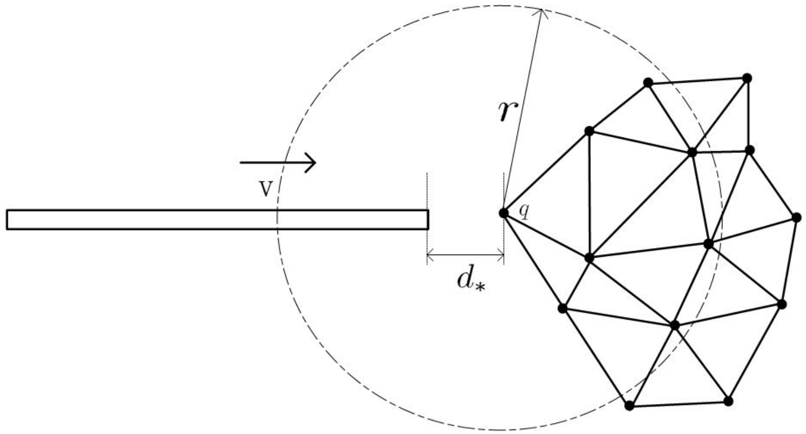
$$C_{\text{area}}\left(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3\right) = \frac{1}{2}\left|\left(\mathbf{x}_2 - \mathbf{x}_1\right) \times \left(\mathbf{x}_3 - \mathbf{x}_1\right)\right| - A_0$$

Methodology

Collision Detection for Tool-Tissue Interaction

Collision Detection for Tool-Tissue Interaction

The collision point is defined as the particle *q* on the mesh when the distance d_* between it and the tool is smaller than a fixed threshold α.



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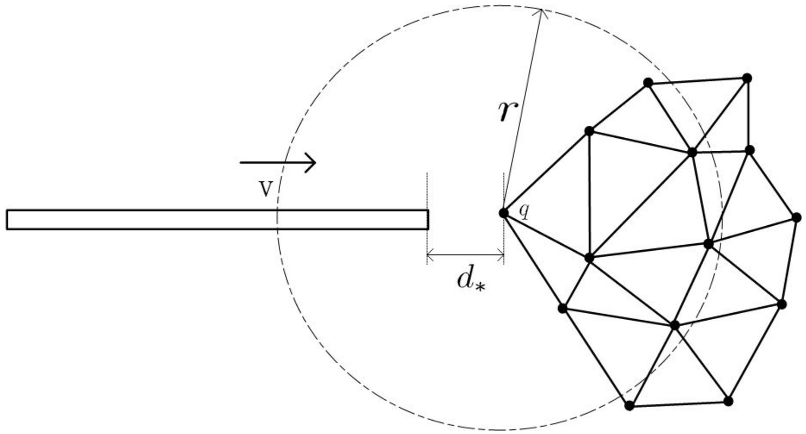

Position update for each particle *i*:

$$x_i^{\mathrm{update}} = \begin{cases} \frac{r - \|\mathbf{x}_q - \mathbf{x}_i\|}{r} d_* \frac{\mathbf{v}_{\mathrm{mani}}}{\|\mathbf{v}_{\mathrm{mani}}\|}, & \text{if } r - \|\mathbf{x}_q - \mathbf{x}_i\| \geq 0 \\ 0, & \text{otherwise} \end{cases}$$

Methodology

Implicit Euler Energy Computation

Contains both the inertial and potential terms:

$$E(x) = \frac{1}{2} \left\| \mathbf{x}^{t+1} - \mathbf{x}^* \right\|_{\mathbf{M}}^2 + \Delta t^2 E_p(\mathbf{x}^{t+1})$$

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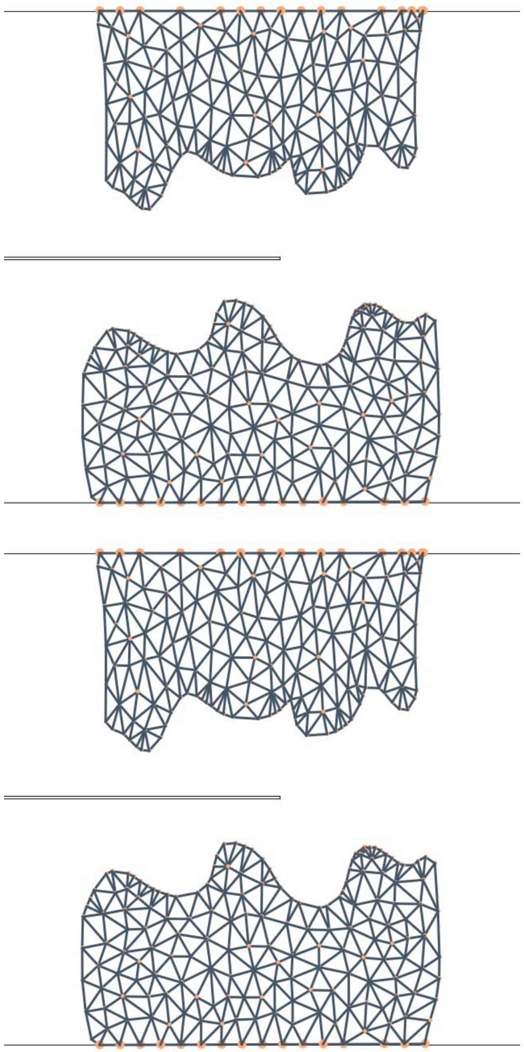
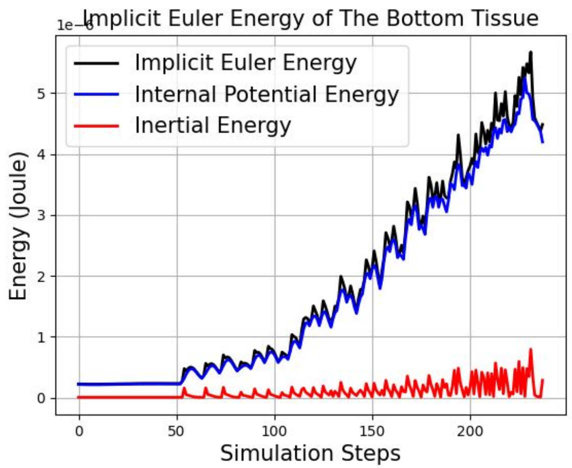
where,

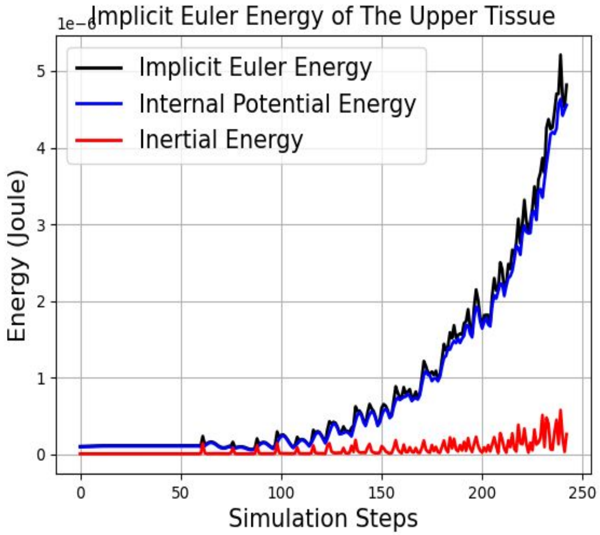
$$\mathbf{C}_i = \left[\mathbf{C}_\mathbf{i}^{\mathrm{Spring}}(\mathbf{x}), \mathbf{C}_\mathbf{i}^{\mathrm{Area}}(\mathbf{x})\right]^T$$

Experiments

Task1: The tool is approaching the bottom/upper tissue

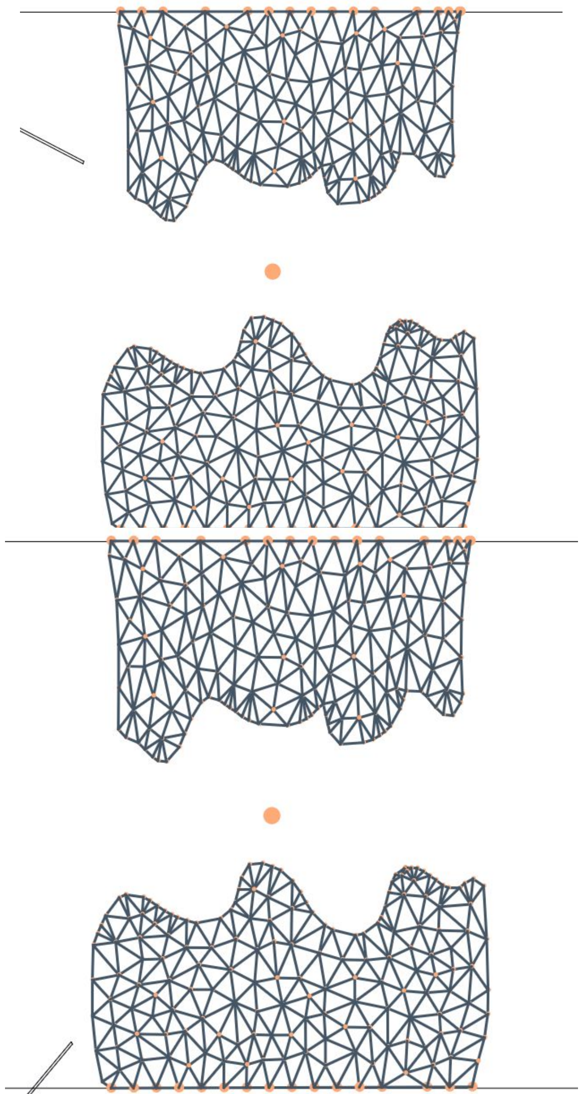


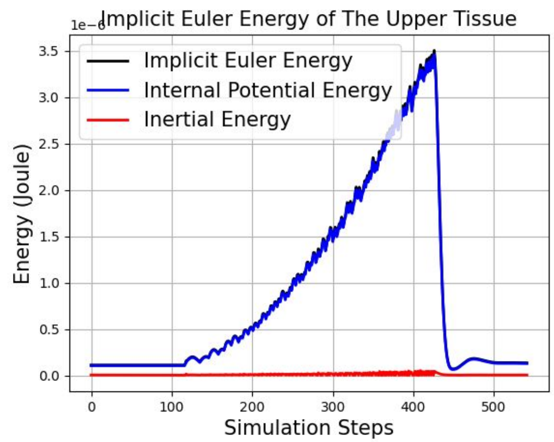


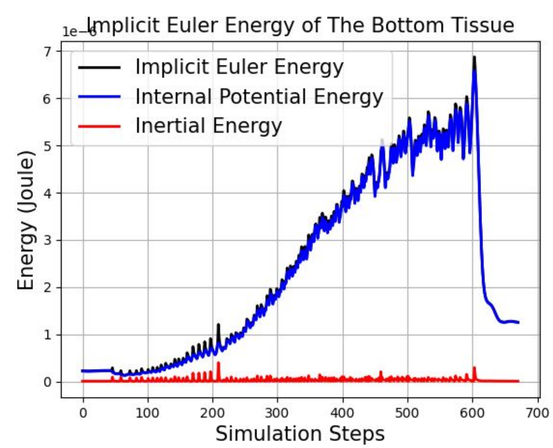


Experiments

Task2: The tool is being inserted from two different angles, aiming at the same target goal.







It is obviously to see the energy variation according to insertion angle.

Conclusion

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- **Simulate the 2D soft tissue deformations**

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Thanks for Listening!

Any Questions?