In Situ Flexible Needle Path Adjustment Modeling and Experimentation

Computer Integrated Surgery II

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Yanzhou Wang, mentored by Prof. Iulian Iordachita and Prof. Russell Taylor

Introduction

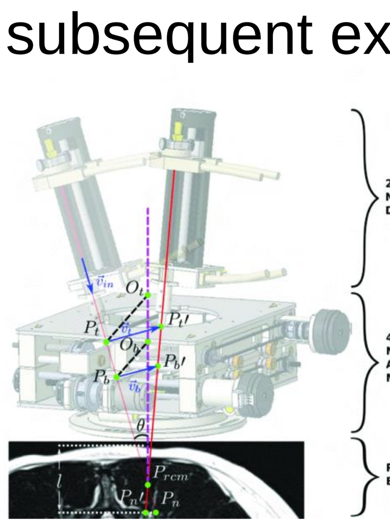
- Interaction between soft tissue and flexible needle is closely examined during needle bending and rotation. A finite element (FE) model is proposed, and the model is evaluated with both tissue phantoms as well as porcine samples under cone-beam CT volumes. A test jig is built to contain test samples and the needle, and generate needle bending and rotation. An image registration algorithm is written to extract motion and model parameters automatically from CT volumes.
- This project aims to improve the feasibility of automated flexible needle insertion by examining commonly practiced needle adjustment procedure during freehand insertion.

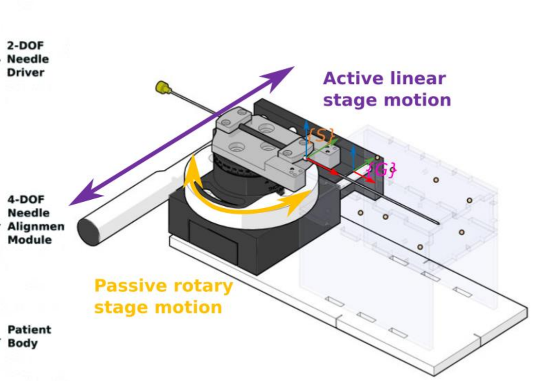
The Problem

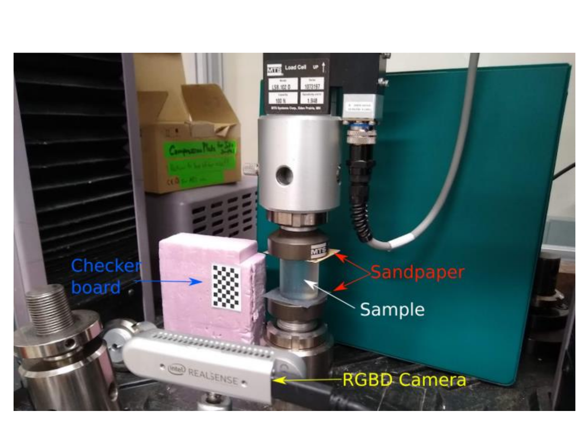
- Automated needle insertion is a challenging problem to be solve due to complex behavior of the soft tissue and the flexibility of needles. For example, our MR-Conditional robot for lumbar injection often cannot drive the needle into the facet joint, due to cumulated error from registration, unmodeled needle-tissue interaction, and so on.
- To prevent a full "reset" of the needle and robot if fault occurs, we explore the option of applying local adjustment of the needle from its base, i.e. to bend and rotate the needle in order bring the tip closer to the target, which is what is typically done by freehand needle insertions.
- In order to predict, and in the future, control the needle tip position, a close examination of the effect of such needle motion is necessary.

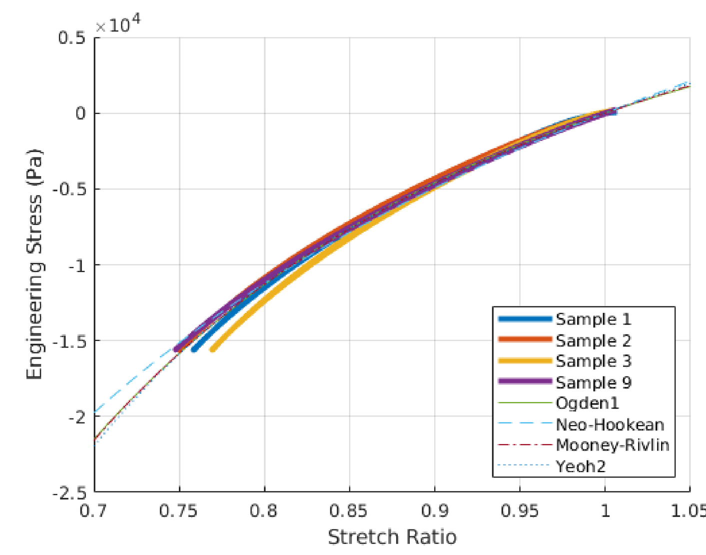
The Solution

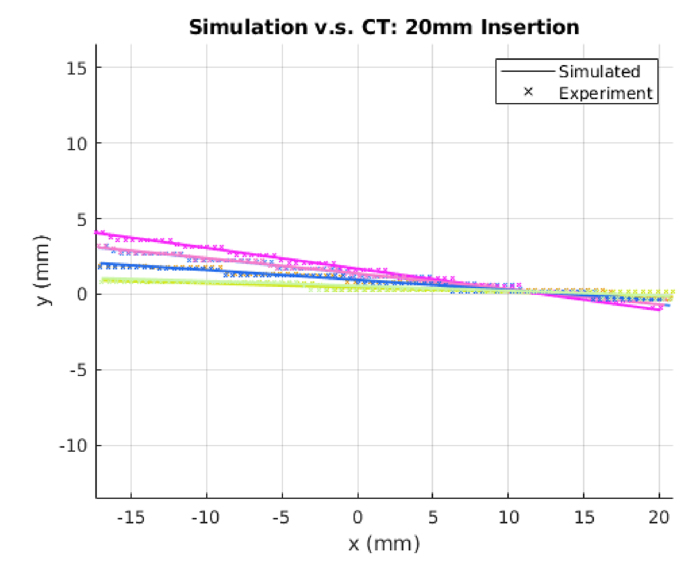
- Interaction between soft tissue and flexible needle during needle bending and rotation is modeled, considering both the needle and tissue mechanical properties. The model is solved using custom FE routine and evaluated using soft PVC and porcine samples.
- A test jig is created to create needle bending and rotation when the needle is inserted into the sample. A CT image registration routine is written to detect the needle shape and needle motion parameters from the steel markers on the jig.
- To establish a "ground truth", a custom mold is built to create consistent PVC cylinders for compression testing, for model verification using the soft PVC tissue phantoms.
- To further evaluate the model performance, porcine samples, whose mechanical properties match closely to those of human skeletal muscles, are used in subsequent experiments.











PVC sample mechanical compressive behavior described with different hyperelastic material models. The FE model is checked against real CT scans using the material properties obtained from compression tests.

Outcomes and Results

- Soft PVC samples' compressive behavior is best described using one-term Ogden model, which is used in FE solution.
- The FE simulation of the needle shape is checked against real CT scans, and shows sub-millimeter accuracy in determining the altered needle tip position and needle shape for both PVC samples and porcine sample.

Table 1: PVC Simulation Result

20mm			40mm			60mm		
d_b	Avg. El. Err	Tip Err	d_b	Avg. El. Err	Tip Err	d_b	Avg. El. Err	Tip Err
0.91	0.02	0.35	0.94	0.03	0.54	0.96	0.02	0.46
2.05	0.02	0.14	2.08	0.04	0.40	1.59	0.02	0.58
3.08	0.02	0.39	3.07	0.04	0.68	2.00	0.02	0.23
4.07	0.02	0.14	4.12	0.04	1.01	2.96	0.02	0.36
3.10	0.02	0.32	3.10	0.04	0.74	4.02	0.03	0.60
2.05	0.02	0.02	2.11	0.03	0.41	3.02	0.02	0.27
1.07	0.02	0.21	1.07	0.02	0.59	2.06	0.02	0.50

Table 2: Porcine Simulation Result

20mm			40mm			60mm		
d_b	Avg. El. Err	Tip Err	d_b	Avg. El. Err	Tip Err	d_b	Avg. El. Err	Tip Err
0.85	0.03	0.37	0.96	0.01	0.03	1.21	0.02	0.04
1.63	0.02	0.34	1.99	0.02	0.06	2.29	0.02	0.04
2.40	0.02	0.37	3.01	0.02	0.06	3.37	0.02	0.14
3.22	0.02	0.18	4.05	0.02	0.01	4.45	0.02	0.30

Future Work

- The needle-tissue interaction model will be extended into a boundary control problem in order to calculate the necessary needle base motions in order to adjust the needle tip to some target location.

Lessons Learned

- Workflow to design and build test setup for motion extraction from CT images.
- Building PVC test samples for MTS compression tests.

Credits

- I did all the above work.

Publications

- A paper is currently under preparation for submission for ICRA 2023.

Support by and Acknowledgements

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