Toward Autonomous Cardiac Catheterization Through a Parametric Finite Element Simulation With Experimental Validation

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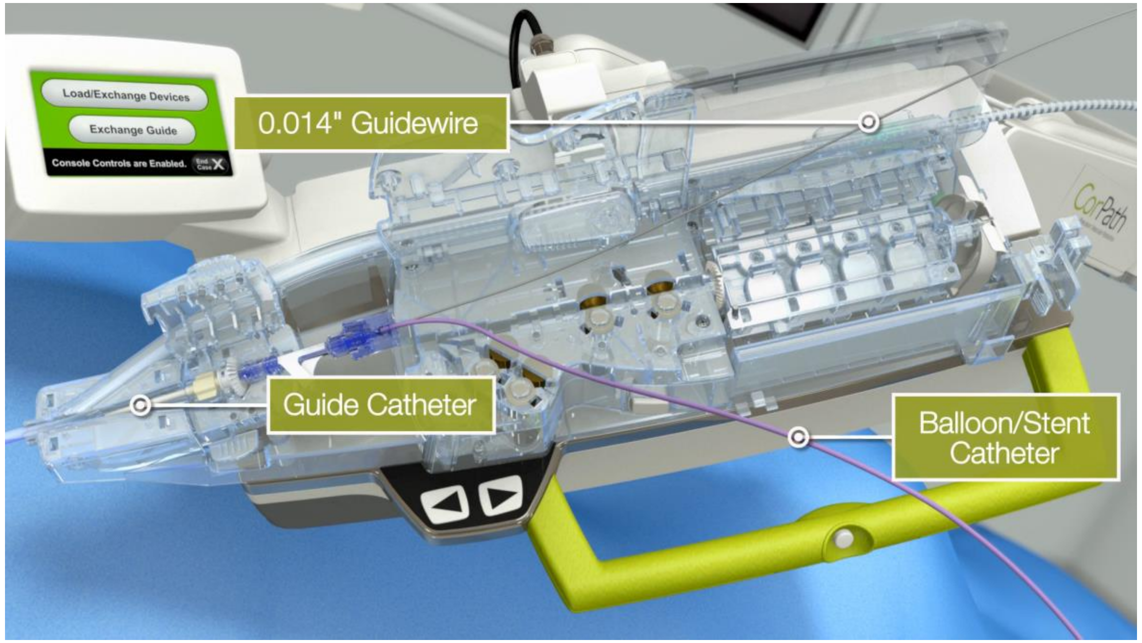
Short resume of the presenter

Majid Roshanfar is a Ph.D. candidate in the Robotic Surgery Lab at Concordia University, Montreal, QC, Canada. He was a fellow of the NSERC CREATE program for Innovation at the Cutting-Edge (ICE) at McGill University (2018-2021) and received the FRQNT scholarship for interdisciplinary research (2021). He has Bachelor's (2014) and Master's (2016) degrees in Mechanical Engineering with honors from the University of Tehran and K.N. Toosi University of Technology, Tehran, Iran. Majid's research has been on the design, modeling, integration, and control of hybrid-driven soft robots for robot-assisted interventional surgery.

Robotic Catheterization



Corindus CorPath System

- Small incision or percutaneous procedures,
- Less blood loss, anesthesia time, and shorter post-surgical recovery time,
- Well-established technique with practice in various applications.

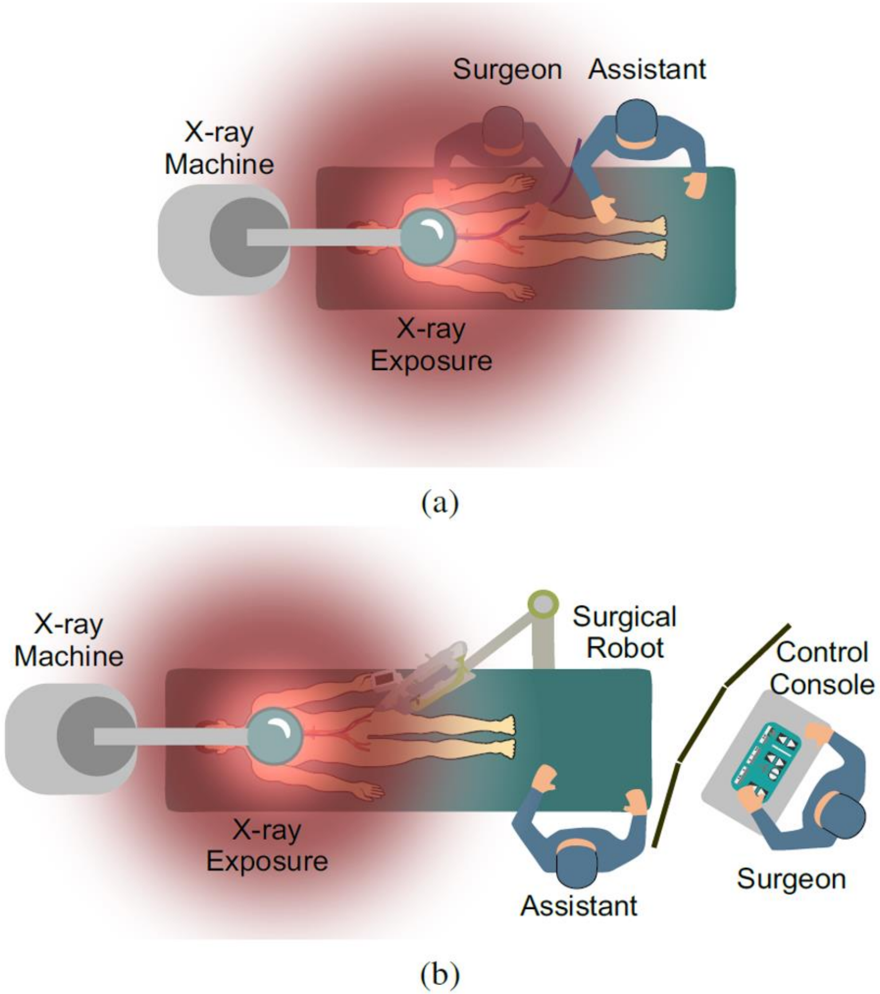
However:

- Requires specialized instruments and techniques,
- Has small workspace for surgeons,
- Requires dexterity and more interaction with anatomy compared to the conventional surgery,
- Has smaller field-of-view → higher risk of human error,
- The catheters are maneuvered from outside the body.

Advantages and Limitations

- Reduce Health Risks for Patients and Surgeons
- Small/No Incision
- Dexterity and Precision
- Shorter procedural time

- Limited force transmission capacity
- Compromise between force capacity and workspace
- Difficulty in steering through complex anatomy
- Risk of contact injury by large contact force



Catheter Insertion Under live X-ray

Hooshiar et al., 2019

Clinical Need

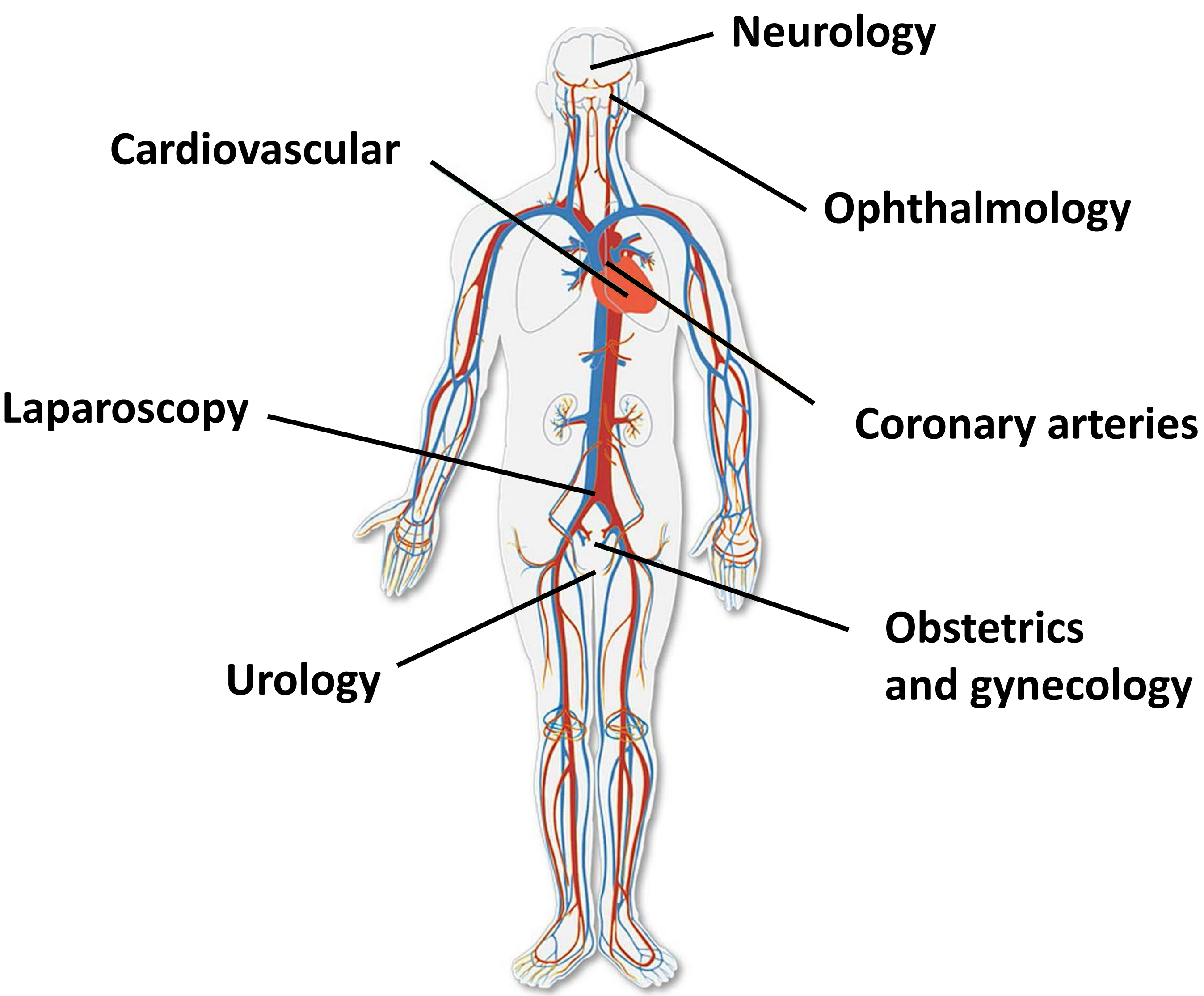
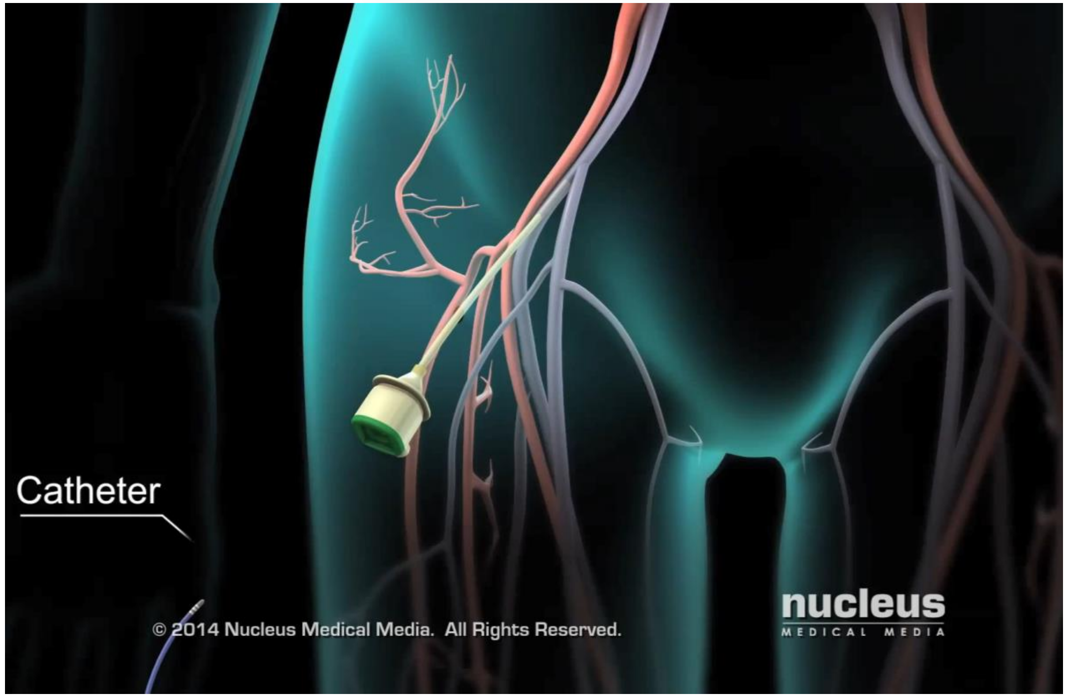


Image: A. Hooshiar et.al (2020)

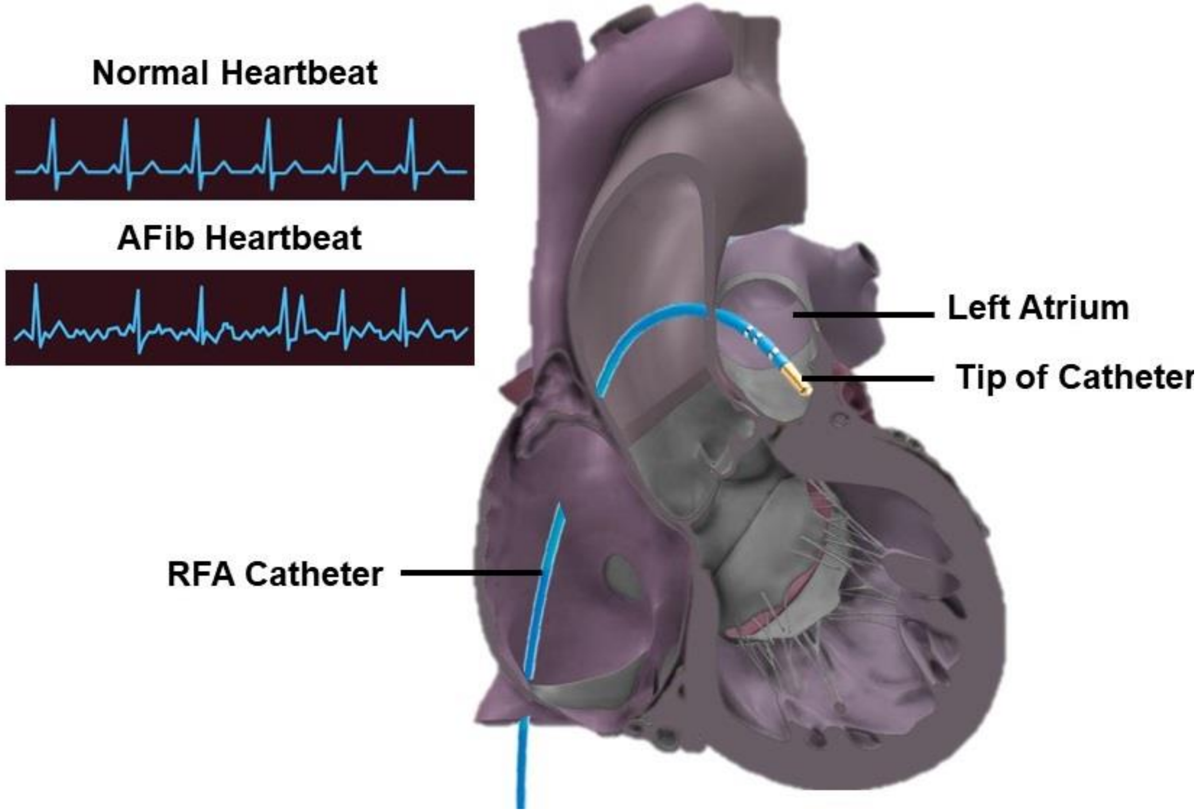
Steerable catheter



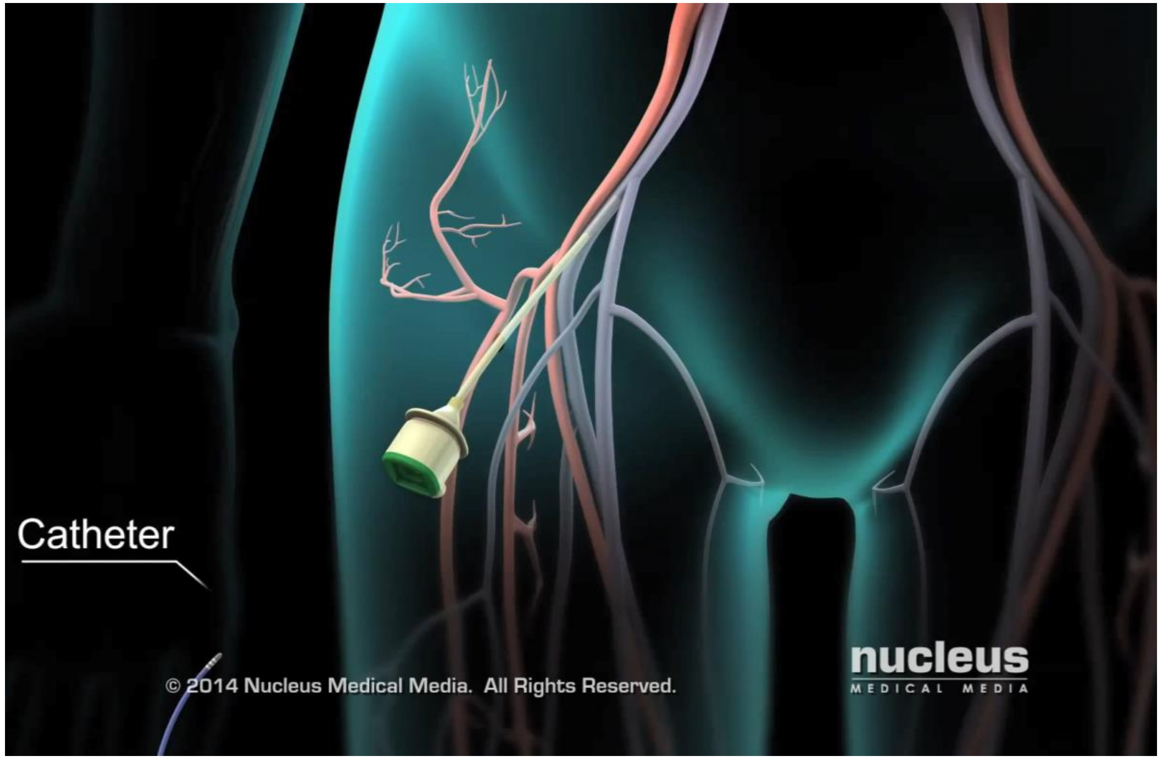
Ablation, Nucleus Medical Media

Radio Frequency Ablation

- Atrial Fibrillation (AFib) is the most common arrhythmia, in which the electrical activity within the atria becomes chaotic.
- In Radio Frequency Ablation (RFA), the arrhythmogenic sites within the cardiac tissue are partially burned off to reduce the undesired pulsation within the cardiac tissue.



3D Heart model from Zygote Media Group Inc.

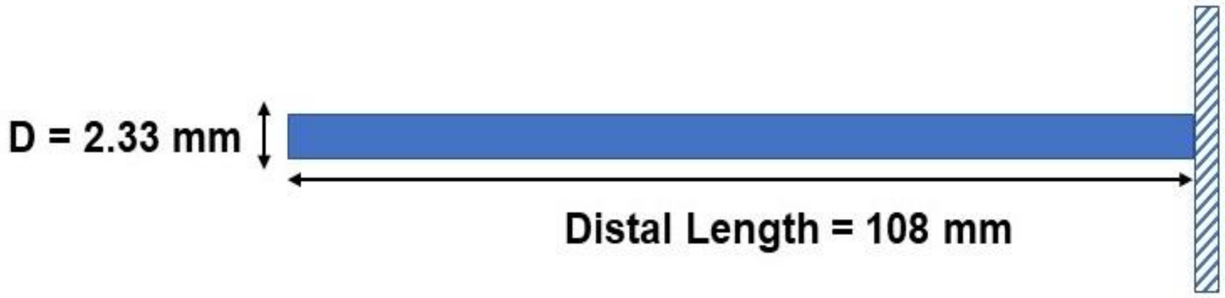


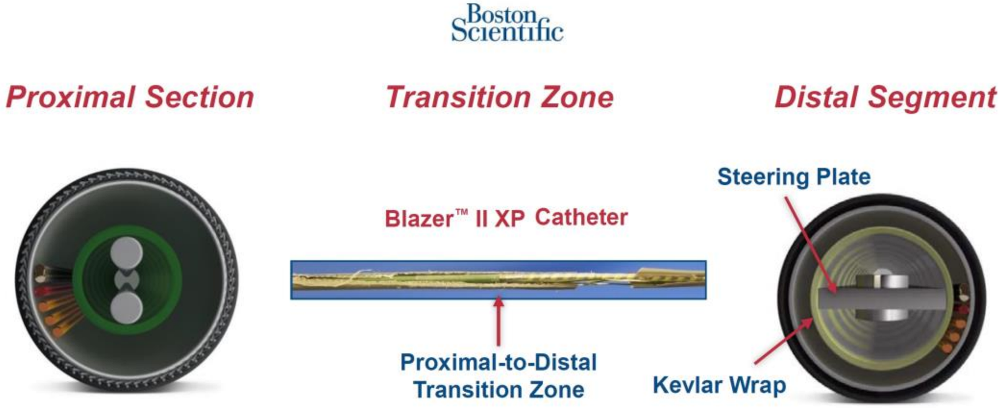
Ablation, Nucleus Medical Media

Parametric Finite Element Model

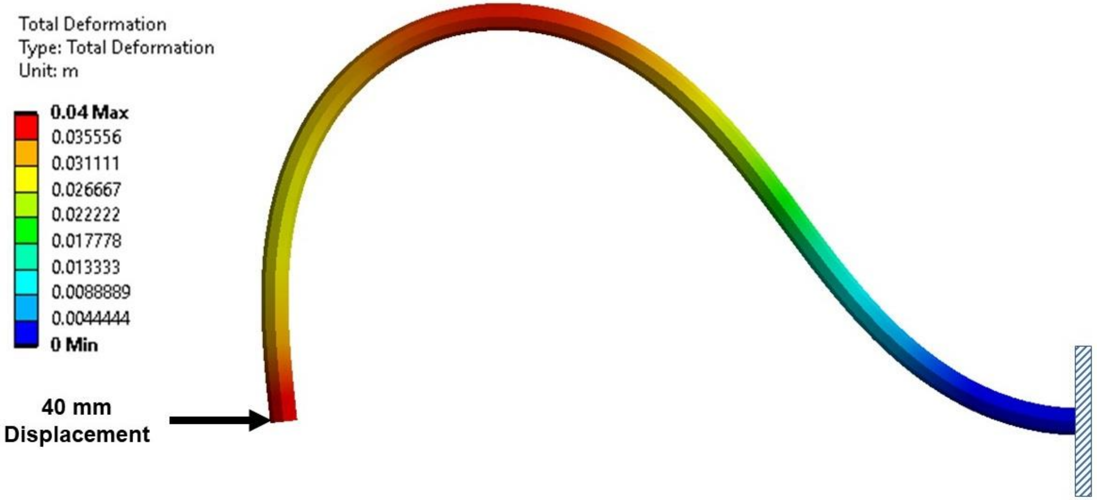
Cantilever beam with a length of L=108 mm and diameter D=2.33 mm

Model of catheter: Blazer II XP, Model 4770THK2, Boston Scientific



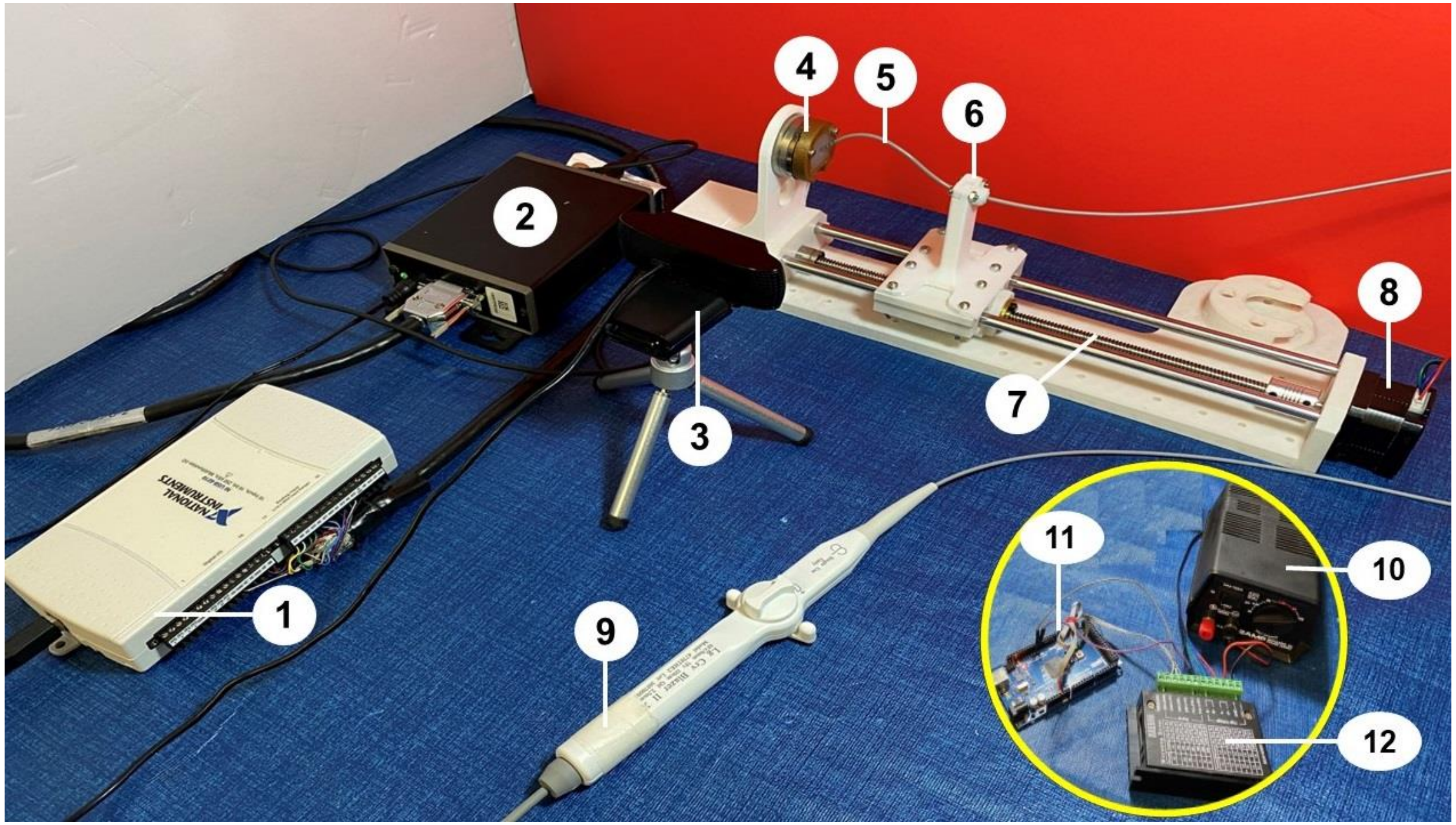


Boston Scientific

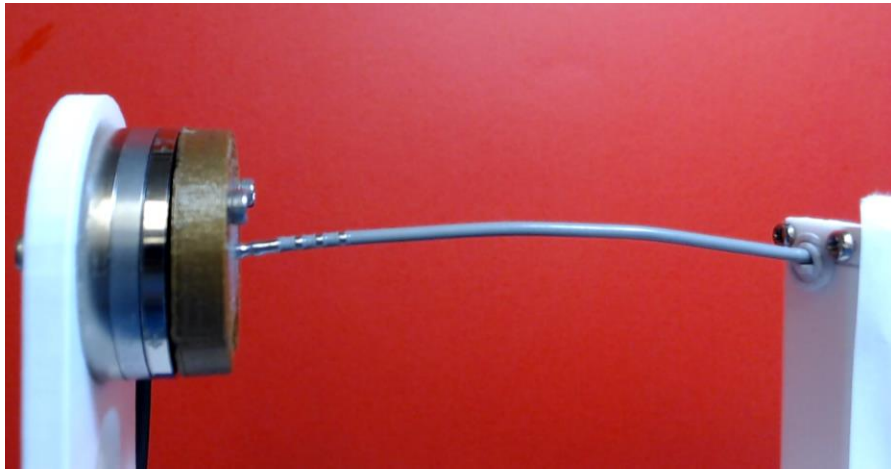


Deformation of catheter

Experimental setup



Experimental setup, (1) data acquisition unit (2) power supply of sensor (3) camera (4) ATI Industrial Automation, F/T Sensor: Mini40 (5) tip of the catheter (6) holder (7) linear actuator (8) Nema 17 stepper motor (9) steerable catheter (10) power supply (11) Arduino MEGA 2560 (12) microstep driver.

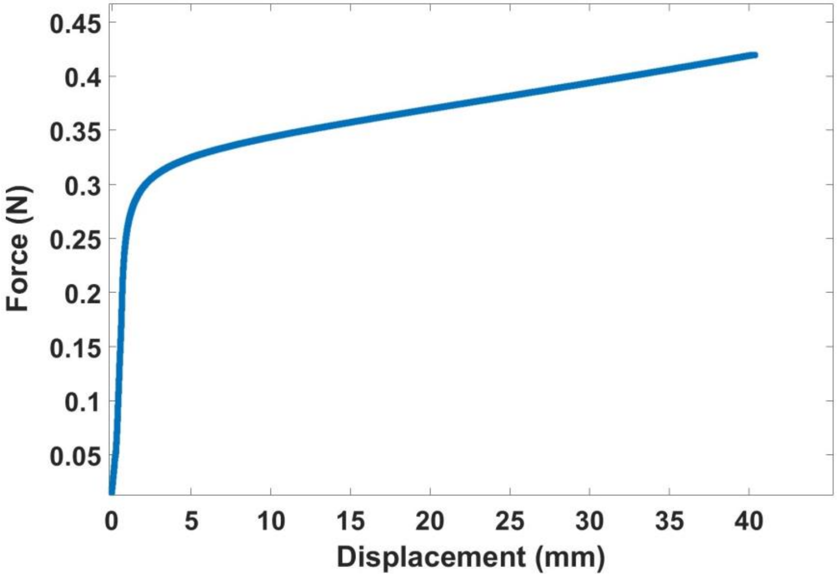


Deformation for the tip of catheter when the catheter squeezed 40 mm to the force sensor.

Validation Study

To validate the parametric simulation and find the material properties, a range for every three parameters is considered as follows:

- Young's modulus ranges from 120 to 200 MPa,
- Poisson's ratio from 0.3 to 0.4,
- Density from 7000 to 8000 kg/m^3.

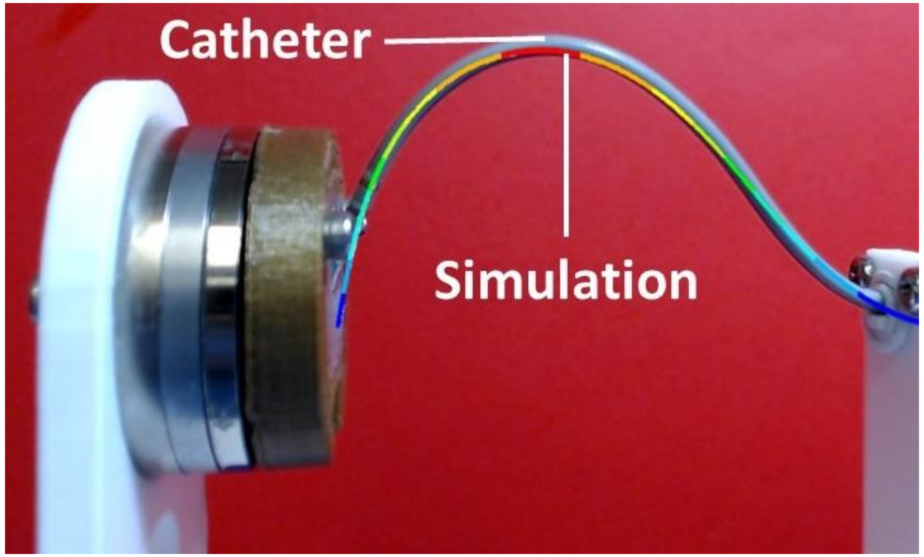


Recorded force during the experiment when the tip of the catheter was squeezed for 40 mm.

TABLE I
PARAMETRIC STUDY EXPERIMENT POINTS

Experiment Points	Density (kg/m^3)	Young's Modulus (MPa)	Poisson Ratio	Reaction Force (N)
1	7500	160	0.35	0.4882
2	7000	160	0.35	0.4881
3	8000	160	0.35	0.4884
4	7500	120	0.35	0.3669
5	7500	200	0.35	0.6096
6	7500	160	0.3	0.4883
7	7500	160	0.4	0.4882
8	7093.48	127.47	0.31	0.3895
9	7906.51	127.47	0.31	0.3898
10	7093.48	192.52	0.31	0.5868
11	7906.51	192.52	0.31	0.5871
12	7093.48	127.47	0.39	0.3894
13	7906.51	127.47	0.39	0.3897
14	7093.48	192.52	0.39	0.5867
15	7906.51	192.52	0.39	0.5870

Comparison of FEM simulation and experimental deformation for the tip of catheter when the catheter squeezed 40 mm to the force sensor.

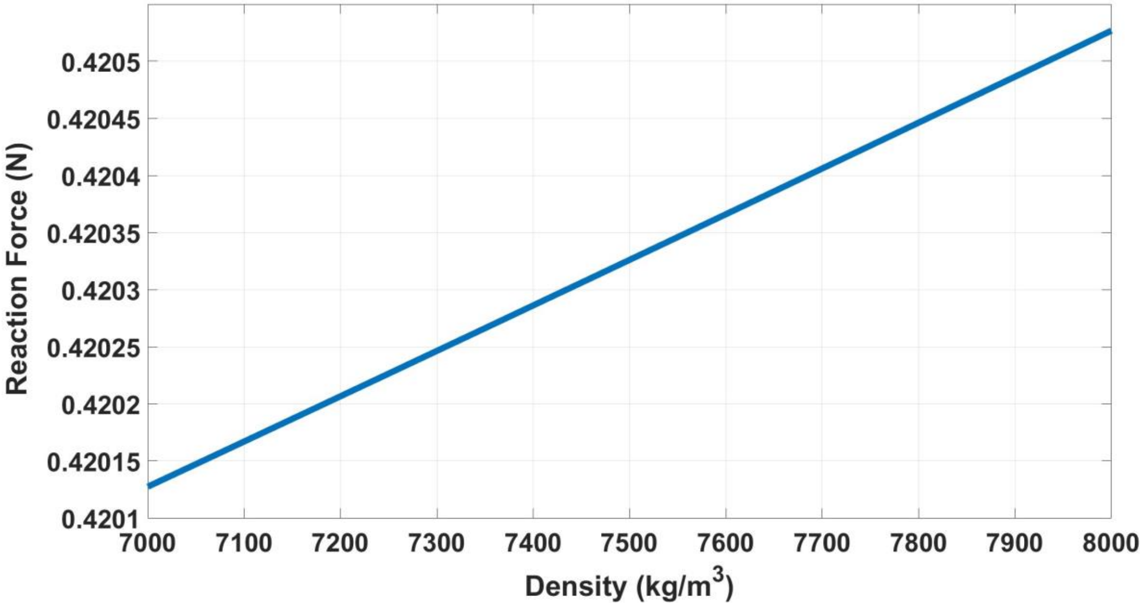


Results

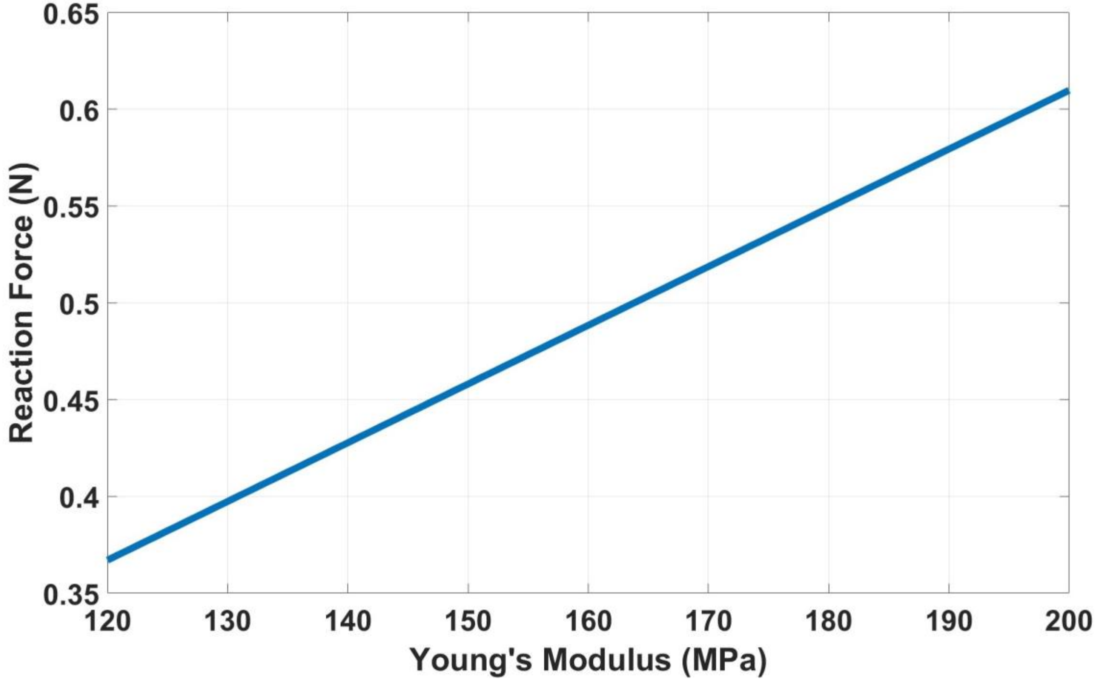
Utilizing ANSYS's Response Surface Optimization (RSO) module, the candidate point is selected with the aim of minimizing the error between the reaction force obtained from the force sensor and the simulation.

TABLE II
MECHANICAL PROPERTIES OF CATHETER FOUND USING THE RSO.

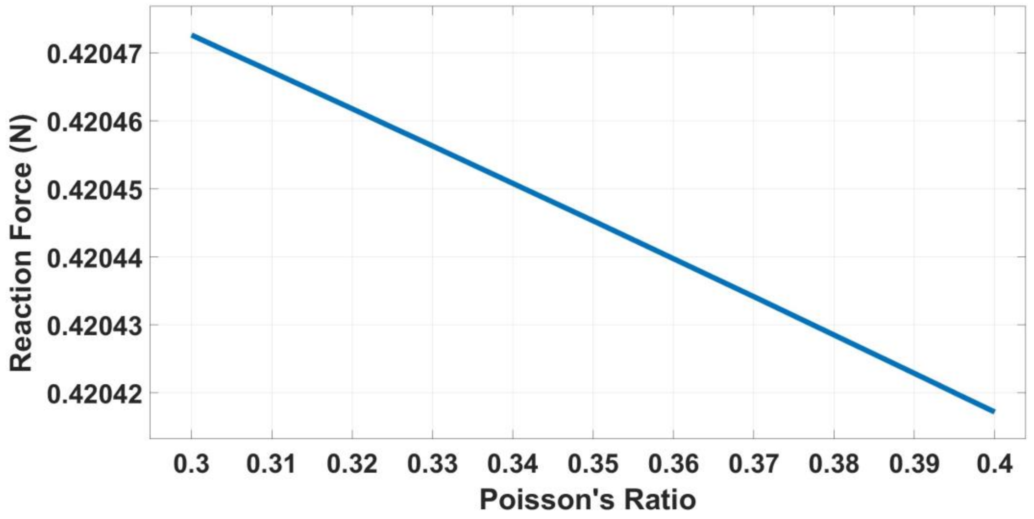
Young's modulus (MPa)	Poisson ratio	Density (kg/m^3)
137.6	0.394	7736



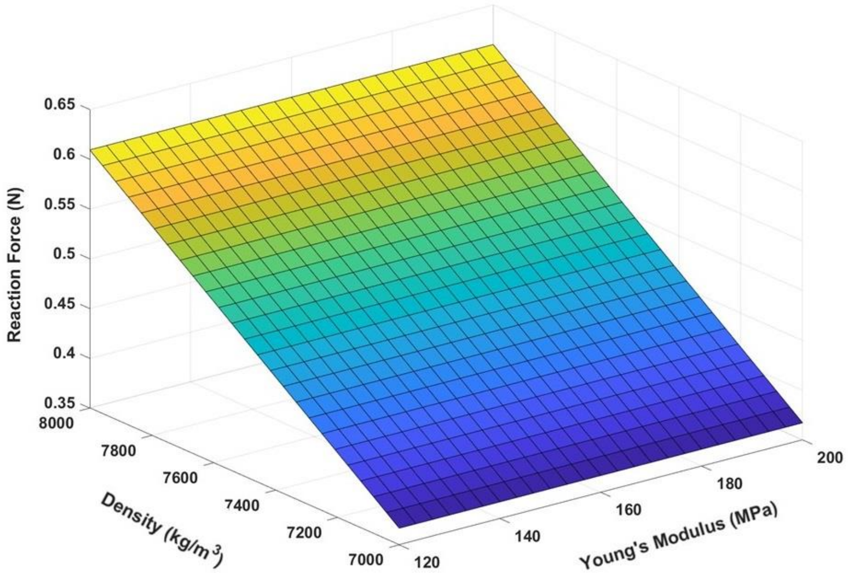
Variation of reaction force by changing the density in the range of 7000 to 8000 kg/m^3 while Young's modulus and Poisson's ratio are set to candidate values.



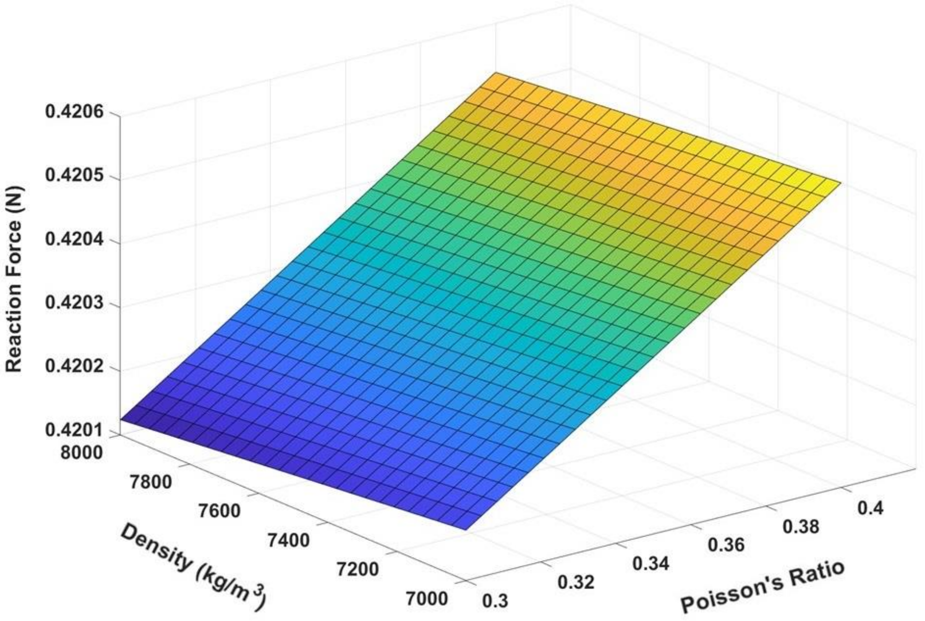
Variation of reaction force by changing the Young's modulus in the range of 120 to 200 MPa while density and Poisson's ratio are set to candidate values.



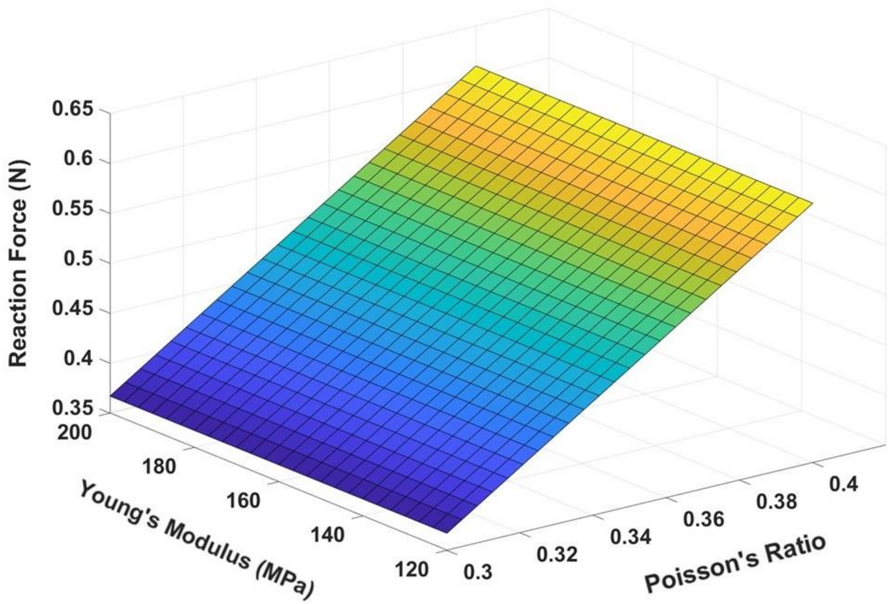
Variation of reaction force by changing the Poisson's ratio in the range of 0.3 to 0.4 while Young's modulus and density are set to candidate values.



Variation of reaction force by changing the Young's modulus and density.



Variation of reaction force by changing the Poisson's ratio and density.



Variation of reaction force by changing the Poisson's ratio and Young's modulus.

Conclusion and Future Work

Conclusion

- The purpose of this study was to simulate a parametric finite element model for a steerable catheter which will be used for the estimation of force during radio frequency ablation procedures,
- The results of the FE simulation were in fair agreement with the reference values obtained from the experiment,
- Based on the outcome of the current study, the proposed method was able to meet both the accuracy and speed requirements for procedures involving robot-assisted autonomous cardiac ablation,

Future Work

- A real-time force estimator is necessary for ensuring the safety and effectiveness of robot-assisted radio frequency ablation,
- A learning-from-simulation model will be proposed to estimate the tip contact force without actually running the simulation in real-time. This feature will enhance the accuracy and precision of minimally invasive procedures for robotic catheter intervention systems.

Acknowledgment

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Thank You