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A Deep Learning Model for Tip Force Estimation on Steerable Catheters Via Learning-from-Simulation

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A Deep Learning Model for Tip Force Estimation on Steerable Catheters Via Learning-From-Simulation

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INTRODUCTION

Atrial Fibrillation (AFib) is the most common arrhythmia among the elderly population, where electrical activity becomes chaotic, leading to blood clots and strokes. During Radio Frequency Ablation (RFA), the arrhythmogenic sites within the cardiac tissue are burned off to reduce the undesired pulsation. Manual catheters are used for most atrial ablations, however, robotic catheter intervention systems provide more precise mapping. Several studies showed excessive contact forces (> 0.45 N) increase the incidence of tissue perforation, while inadequate force (< 0.1 N) results in ineffective ablation. Fig. 1 shows a schematic of a cardiac RFA catheter used for AFib treatment. For robot-assisted RFA to be safe and effective, real-time force estimation of catheter's tip is required. As a solution, finite element (FE) analysis can provide a useful tool to estimate the real-time tip contact force. In this work, a planar FE model of a steerable catheter was first developed with parametric material properties. After that, a series of simulations based on each mechanical property was performed, and the deformed shape of the catheter was recorded. Next, validation was conducted by comparing the results of the simulation with experimental results between the range of 0-0.45 N to determine the material properties. Despite the previous work, which was a study to estimate the tip contact force of a catheter using a deep convolutional neural network [1]–[3], the main contribution of this study was proposing a synthetic data generation, so as to train a light deep learning (DL) architecture for tip force estimation according to the FE simulations. Due to the availability of real-time X-ray images during RFA procedures (fluoroscopy), the shape of the catheter is available intraoperatively. The proposed solution provides enough data for DL methods and demonstrates the possibility of replacing quick and light learning-based methods instead of slow simulations.

MATERIALS AND METHODS

The catheter was modeled as a 2D cantilever beam with a length of $L = 108$ mm and diameter $D = 2.33$ mm. These are the dimensions of the available catheter (Blazer II XP, Model 4770THK2, Boston Scientific). Due to the different materials used to prototype catheters, the equivalent Young's modulus, Poisson's ratio, and density are considered as parameters in the simulations. Then based on the deformation of the catheter during the experimental setup, the values for these parameters are tuned. During the experiment, the tip of the catheter was 40 mm squeezed, and the reaction force at the base was recorded. Homogeneous Dirichlet and Neumann boundary conditions were applied at the right-most of the model to simulate the cantilever condition for the distal shaft of the catheter. The model was solved with 108 elements and with a large deformation assumption. To validate the parametric simulation and find the material properties, a range for every three parameters is considered. Young's modulus ranges from 120 to 200 MPa, Poisson's ratio from 0.3 to 0.4, and density from 7000 to 8000 kg/m^3. The experimental setup in Fig. 2 mimics the catheter simulation. Before the experiment, 108 mm of the catheter tip was measured and fixed in the holder of the linear actuator. The linear actuator was 3D printed in a way to align the center of the holder and 6-DoF force/torque sensor (ATI, Mini40). Next, the catheter tip was squeezed against the force sensor, which was mounted at the end of the linear actuator. Simultaneously, a camera perpendicular to the deflection plane was used to record the deflection of the catheter. Fig.3(a) shows the recorded unidirectional force during the experiment and Fig.3(b) compares the result of the experiment and simulation. By utilizing ANSYS's response surface optimization (RSO) module, while ignoring the hysteresis effect during loading and unloading, the candidate point is selected with the aim of minimizing the error between the reaction force obtained from the force sensor and the simulation. After the optimization, Young's modulus, Poisson ratio, and density are set to 137.6 MPa, 0.394, and 7736 kg/m^3, respectively [4]. The difference in tip force error between the simulation and the physical model was below 0.01 N.

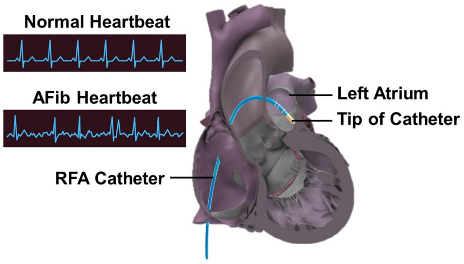


Fig. 1 Ablation catheter during RFA procedure (3D Heart model from Zygote Media Group Inc.).

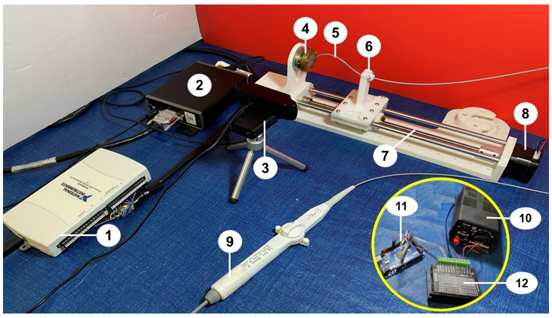
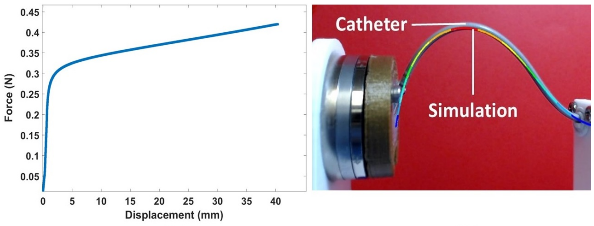


Fig. 2 Experimental setup, (1) data acquisition unit (2) power supply of sensor (3) camera (4) force/torque sensor (5) tip of the catheter (6) holder (7) linear actuator (8) stepper motor (9) steerable catheter (10) power supply (11) Arduino (12) microstep driver.



(a) (b)

Fig. 3 **(a)** Recorded force **(b)** Simulation and experiment comparison.

Considering FE simulation as a reference, the point is to create a model derived from the attained deflections and forces. In the previous studies, an effort was made to develop an experimental setup and carefully compile the required data by mechanically synthesizing different catheter deflections. However, simulation data can facilitate the data compilation process, as well as provide greater flexibility in producing various deflections. The intended model is meant to map the shape of deflections generated by the simulation to their corresponding forces. The dataset comprises 10100 greyscale images with the shape of 224×224. The total forces associated with each image is a vector norm attained from the forces along the x and y direction with $min = 0.015$, $max = 0.419$, $std = 0.05$, and $mean = 0.362$. Given that, 70% of data was dedicated to the training set while the rest went for the test and validation set evenly. The goal is to create a model based on an image regression to map the input simulated images to the total force space. Inspired by [1], [2] a light-weight convolutional neural network is designed to model the data since the input images do not comprise complex shapes and regions. Input image (Fig. 4) is fed to the first convolution layer with 64 filters of size 7×7 and stride 2 followed by a max pooling 3×3 and stride 2. The output goes into 2 successive convolutional blocks with residual connections. Each of those blocks contains 2 convolution layers with 64 filters of size 3×3 along with a residual connection that adds the input channels to the output of the block. However, the first convolution layer of the first block diminishes the size of inputs with a stride 2 which reduces the input with size 224×224 to 64 feature maps of size 28×28. Next, a global average pooling layer flattens the aforementioned feature maps into a vector that goes to a dense layer with 16 neurons. The ReLu activation function is applied to all convolutional and dense layers except the output layer which is one neuron to generate total forces. The architecture parameters are tuned by minimizing the Mean Square Error (MSE) loss function using Root Mean Squared Propagation (RMSprop) optimizer.

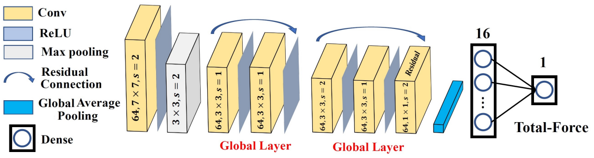


Fig. 4 Convolutional graph of the model inspired by the Y-Net [1].

TABLE I Benchmark for comparing the results with previous studies.

Models	inp	MSE	MAE	RMSE
Y-Net	3	2.83e-05	0.0039	0.005
ResNet	2	-	-	0.025
SimResNet	1	1.26e-05	0.0033	0.003

RESULTS

A convolutional graph trained on simulated data shows that synthetic data can be fed into a model. DL graph was trained with the batch size 32 and learning rate $lr = 0.001$ in 50 epochs. To keep track of overfitting, the model was validated on the validation set every epoch. Table I reports the performance of the trained model in the inference stage on the test set using the following metrics: Mean Absolute Error (MAE), MSE, and Root Mean Square Error (RMSE). For sake of a benchmark, the trained model was compared with the Y-Net [1] and ResNet [2] which were trained on a realistic dataset, as indicated in the references. The trained model of this work is called "SimResNet". SimResNet can learn total forces precisely without overfitting. Comparing the SimResNet with the Y-Net and ResNet, the obtained results are matched with the reported results. However, the MAE for SimResNet is slightly smaller than the other models. This can stem from the fact that in contrast to SimResNet, the output of Y-Net and ResNet are in a 3D and 2D force space respectively.

DISCUSSION

Through learning-from-simulation, this study proposes a DL approach for estimating tip force on steerable catheters. To determine the catheter's design parameters, FEM simulations were conducted and model was trained using the data extracted from the simulation. To make the results more applicable in real-world scenarios, shape estimation can be done at different angles of the knob to evaluate the effect of steering on the estimated tip force.

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