Finite-Element Dynamics of a Tendon-driven Eversion Growing (Vine) Robot Using SOFA-Framework

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INTRODUCTION

Soft robots provide a safer interaction with the human body [1] compared to rigid systems. For this reason, soft robots have been proposed for several medical applications. The come in a variety of forms and operate via actuation methods inspired from nature. Specifically, soft eversion growing, or vine, robots are inspired from the growth of plants [2]. These robots change their length and steer via hydraulic or pneumatic actuation, avoiding relative motion between robot body and its surroundings. Specifically, everting robots elongate via "unfolding" material at their tip.

The use of mathematical models for growing robot's mechanics helps understand their behaviour as a first step to build control algorithms. Simulation Open Framework Architecture (SOFA) is an open-source library to simulate physical interactions [3]. SOFA has been extensively applied in surgical training, anatomy modelling, modelling of tissue-instrument interaction, and simulation and control of soft robots. Nevertheless, there is no specific research on the FEM-based modelling of everting robots to simulate their growth and physical properties.

This research is the first to propose such an approach, using our everting surgical robot prototype, MAMMOBOT [4] as the proof-of-concept platform, whole system described in Fig. 1. This work presents growing and steering of the such a prototype within the SOFA framework.

MATERIALS AND METHODS

The simulated model of the MAMMOBOT is divided into two different subsystems which its correspondent CAD model: **a)** Self-growing sheath and **b)** Tendon-driven steerable soft catheter (Fig. 2). Each of the subsystem where independently modelled and tested using different experimental set up and lastly were placed together as in our prototype. The robot controller in SOFA was modelled using available Python bindings, which helped to design the different experimental setups and collect the data. The list of the experiments performed to validate the FEM model for MAMMOBOT are listed below. We performed all the experiments for both the real system and the simulation, mimicking every possible variable:

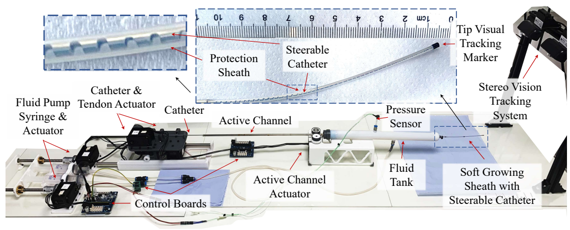

Fig. 1 MAMMOBOT real-system design and its key element

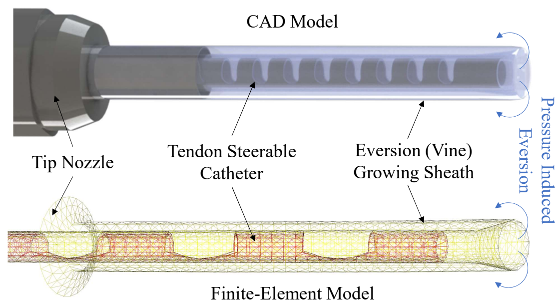

Fig. 2 The MAMMOBOT tip consists of a soft growing sheath whose inner lumen is occupied by a steerable catheter to perform safe steering within branching lumen.

The first system we validated was the catheter. For that, the tendon driven catheter was placed in the simulation without initial pulling. Each step we increased the length of the pulled tendon and let the system to reach equilibrium.

Secondly, we designed an experiment to test the sheath simulated model. The sheath was first grown to same length for both the simulation and the real-system. Once the maximum length was reached, we reduced the internal pressure of the sheath to 110kPa and let the sheath bend due to gravity. We increased the value of the pressure by 10kPa every step, to a maximum of 150kPa, and we record the maximum bending angle of the system after reaching equilibrium.

Once both subsystems were validated with the previous experiment, we embedded both in a single simulation scene and validate the full system. Starting from the

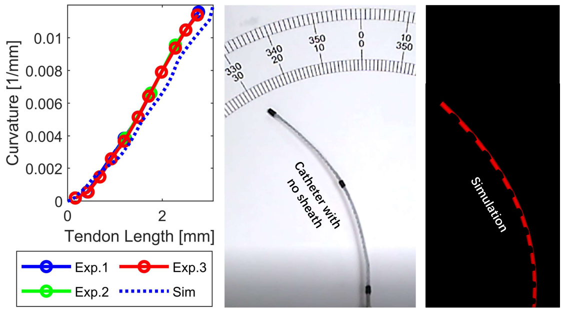

Fig. 3 The curvature of steerable catheter vs change of tendon length

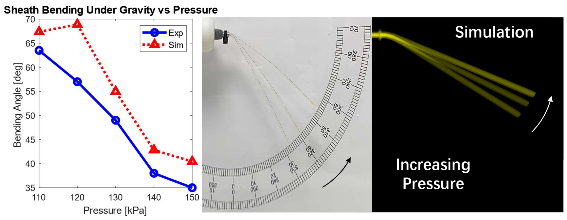

Fig. 4 The bending angle of the growing sheath under gravity for different values of the internal pressure

initial position of the system, the full system was grown simultaneously with a constant base velocity and sheath internal pressure. Once the full system was grown to its full length, the internal total pressure was dropped to 110kPa and the catheter tendon was pulled to its maximum length (3.98mm). The system was left to reach equilibrium and, then, pressure was increase similar to the previous experiment, to a maximum of 150kPa.

RESULTS & DISCUSSION

a) Tendon modelling for steerable catheter.: The simulations for the tendon pulling experiments showed similar behaviour as the one from the real system. The data can be seen in Fig. 3, and shows an almost linear change on the curvature. There was a higher deviation observed at higher values of tendon pulling, however the MAE (Mean Absolute Error) for the whole experiment was $7.32 \times 10^{-4} mm$.

b) Sheath bending angle under gravity.: Simulated and real sheath behaved similarly in the following experiments. Increasing the pressure made the sheath to straighten whereas reducing the initial bending angle generated by gravity, see results in Fig 4. Even though, there is a small offset in the results between both cases the MAE for this experiment was 6.39°.

c) Full system under variable pressure.: This last experiment analysed the effect of pressure on the catheter stiffness, that we related in the previous sheath experiment to have a straightening effect on the sheath. As it can be seen in Fig. 5, the increase of pressure generated a stiffer full system, decreasing the total maximum curvature of it. Real and simulated systems showed similar behaviour on the linear fitting of the data, with a small initial offset of $-1 \times 10^{-4} mm^{-1}$ on the simulation.

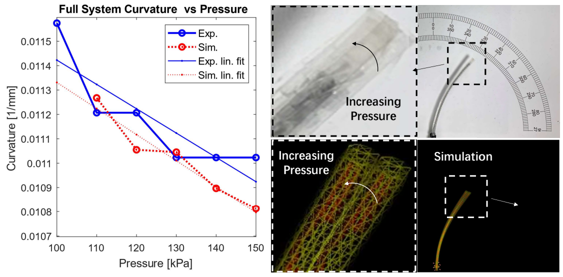

Fig. 5 Curvature change of growing robot with maximum tendon pulling under different pressures.

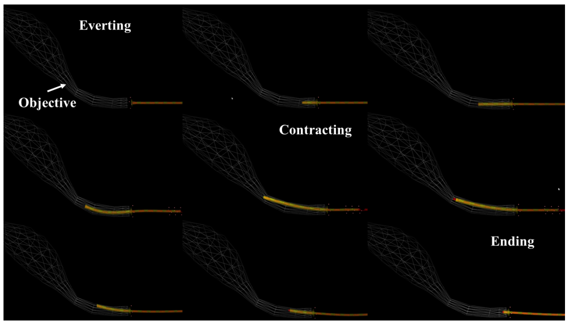

Fig. 6 Navigation scene through the mammary duct. The image sequence shows the eversion and the contraction, after reaching its objective, of the MAMMOBOT.

d) Navigation through a mammary duct: . Implementation of a navigation scene trough the mammary duct. We observe the system everting and contracting successfully, sequence of images in Fig. 6. This scene established a starting point from further research on navigation control.

CONCLUSION

In this paper, we present a SOFA simulation scene of a tendon-driven steerable eversion growing robot and the comparison with its real counterpart. The different experiments show that the FEM model for each subsystem has a similar behavior when independently analysed. Pressure showed to have a measurable impact on the system stiffness, reducing the total curvature $\approx 5\%$ over the whole 40kPa change. Additionally, the simulated system showed the capacity of navigation through a model of a mammary duct inside SOFA. In conclusion, the results of the validation experiments show a successful implementation of a FEM model for eversion growing robot.

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