A Physical Simulator Integrated with Soft Sensing for Mastering the Manipulation of Vascular Structures in Robotic Surgery

Andrea Mariani, Dario Galeazzi, Selene Tognarelli and
Arianna Menciassi

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A. Mariani, D. Galeazzi, S. Tognarelli, A. Menciassi

The BioRobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy
an.mariani@santannapisa.it

INTRODUCTION

Robot-assisted minimally invasive surgery requires the surgeon to learn the new control dynamics of the surgical instruments and, usually, how to deal with the loss of haptic feedback. Indeed, excessive forces applied to delicate tissues – as blood vessels – may cause dramatic intraoperative events, such as major bleeding [1]. Training plays a paramount role to prevent the onset of such adverse events. Nowadays, simulation has come to the forefront to acquire technical skills since it excludes patients from the learning stage. The ideal simulator for surgical training should be able to reproduce the target anatomy with high-fidelity [2]. This is even more fundamental if its aim is teaching tissue manipulation. In this context, tool-tissue interaction and consequent tissue deformation need to be fully realistic [3]. Secondly, the ideal simulator should provide objective assessment of the skill that the simulator is meant to teach [4].

In this work, we introduce a sensorized physical simulator that could be helpful in teaching novices how to reduce tension on vascular structures. On the one hand, physical simulators can reproduce tissue interaction with higher realism than virtual or computer-based simulators. On the other hand, sensorization can guarantee quantitative metrics to assess the surgeon's practical skills and possibly to provide trainees with concurrent (i.e., real-time) feedback to optimize learning.

MATERIALS AND METHODS

Design and fabrication – We focused on robot-assisted thoracoscopic surgery (RATS) to define the target anatomy to simulate. This choice was motivated both by the criticality of tissue manipulation in this kind of procedures and by the expertise of our clinical partner (i.e., Prof. Franca Melfi and her robotic surgery team at the University of Pisa). Indeed, they often require the application of a mechanical stapler on major blood vessels to isolate the lobe to operate. During this task, the most common error for novice surgeons is the exertion of excessive tension on blood vessels [5]. This can lead to the rupture of blood vessels and thus to severe bleeding. In robot-assisted lung lobectomy, vascular injuries are reported in 2.4% of total cases and 87% of such intraoperative events lead to a conversion to open thoracotomy [6]. Specifically, we selected the left inferior pulmonary vein (LIPV) as the vascular structure to simulate. Fig. 1A visually summarizes the fabrication and sensorization of the LIPV simulator.

In details, to create an anatomically accurate model, computed tomography images of an adult human thorax from 3D Slicer library were analyzed. The LIPV simulator was fabricated using the cast molding technique. The mold was designed using SolidWorks software moving from the 3D Slicer segmentation of the LIPV as a reference. Literature data regarding LIPV dimensions were considered to refine the model [7]. The mold was then printed in resin with a ProJet MJP 3600 max machine (by 3D Systems, Rock Hill, SC). Silicone Ecoflex-30 (by Smooth-On, Macungie, PA) was used for the simulator casting. This material was chosen as its elastic modulus is close to the one of pulmonary veins [8].

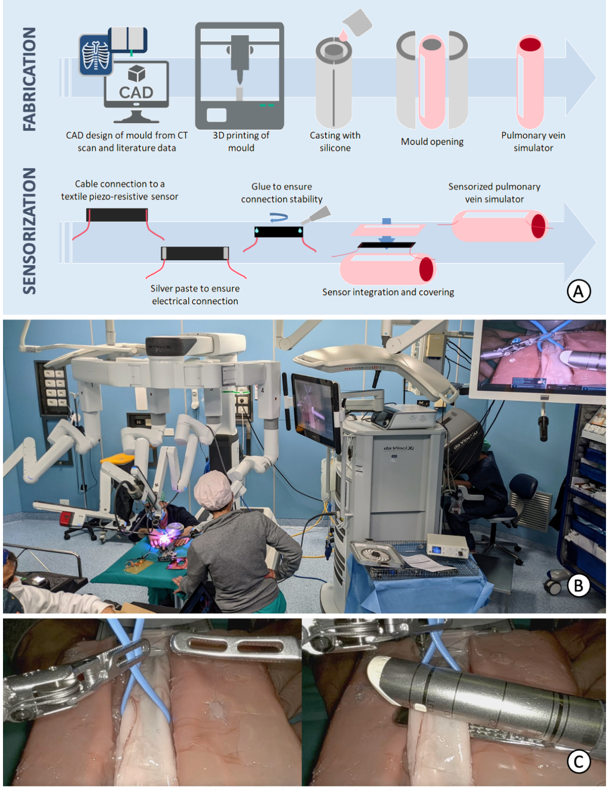

Figure 1. A) Fabrication and sensorization processes. B) A da Vinci Xi Surgical System was used for the preliminary validation of the simulator. C) Two snapshots from the task execution: the surgeon initially passes a blue vessel loop under the vein simulator (left), and later inserts the robotic stapler while raising the vein by taking advantage of the loop (right).

Severe bleeding of blood vessels is associated to excessive strain [1]. Thus, our sensorization was meant to sense the longitudinal strain ε applied to the vein simulator. We aimed at performing such a sensorization without compromising the realism of the simulator. For this reason, we resorted to soft sensors. Specifically, highly stretchable textile sensors were considered since they can be easily integrated into elastic structures and they also provide a cheap solution. In particular, the conductive polymer LG-SLPA (by Eeonyx Corporation, Pinole, CA) was chosen. The textile was integrated to the simulator by using silicone glue. The conductive polymer LG-SLPA behaves like a variable resistor. It was integrated in a simple voltage divider configuration and an Arduino Mega 2560 was used to power the circuit and to read data. To characterize the sensor, a VT-80 Linear Stage (by Physik Instrumente, Karlsruhe, Germany) was used to impose a linear longitudinal strain to the LIPV simulator. To compute the characterization curve of the sensor, linear interpolation was later applied.

Preliminary validation – We focused on the *construct validity* of the simulator (i.e., its capability to distinguish between users with heterogeneous levels of expertise). The experiments were performed using a da Vinci Xi Surgical System (by Intuitive Surgical Inc., Sunnyvale, CA) (Fig. 1B). The surgical instrument mounted on the left patient-side manipulator was a prograsp forceps. On the right manipulator, there was a tip-up fenestrated grasper, later substituted with a stapler 30 at the end of the task. The LIPV simulator was integrated with a clamping system to pre-tension the vein as in physiological conditions (ε=0.13) and a silicon-based support board. This study involved a task resembling the LIPV isolation and stapling. A video showing a repetition of the tasks is available at https://bit.ly/3Lc3ona. This task required to: a) pass a vessel loop under the LIPV to later raise the LIPV (Fig. 1C, left), and b) insert the robotic stapler under the LIPV (Fig. 1C, right). Four users with medical background and different levels of RATS expertise joined this study. This group included: a surgeon and proctor (MAS) with more than 20 years of experience in RATS, an expert surgeon (EXP) with 5 years of experience in RATS, a surgeon (SUR) with a single year of experience in RATS, a surgical resident (RES) with no specific experience in RATS, yet surgical education. Each user performed the task 3 times. Strain values were recorded along each task repetition and the maximum strain applied to the vessel during the task was computed and averaged across the 3 repetitions (ε_{max}).

RESULTS

Sensor characterization – The characterization test of the sensorized simulator showed a linear behavior of the resistance variation with respect to the longitudinal strain, with the presence of a small hysteresis (Fig. 2A). The root mean squared error (linear interpolation) was 0.03, corresponding to 4% of the full-scale output. It was considered sufficiently small for the application.

Construct validity – Fig. 2B shows ε_{max} as a function of the user's expertise. It is possible to notice a distinct trend: the higher the experience, the lower the maximum strain applied to the vascular structure.

DISCUSSION

This work introduces an anatomy-based simulator of pulmonary vein integrated with soft textile sensing. Sensor data can be processed to extract a simple metric related to the vessel strain and this information was proven to objectively discriminate medical users with heterogeneous levels of expertise. This feature (*construct validity*) plays a relevant role in training and education, as it can be used to assess when the trainee has learnt how to master a certain skill. The possibility to assess skills by using a sensor makes the evaluation totally objective, as well as independent from the presence of a proctor. In addition to skill assessment, sensor data can be used to provide a warning feedback to the trainee (e.g., using a buzzer). A strain-based feedback could optimize learning the robot-assisted manipulation of vascular structures (where haptic feedback is usually missing) by teaching the maximum strain that can be applied.

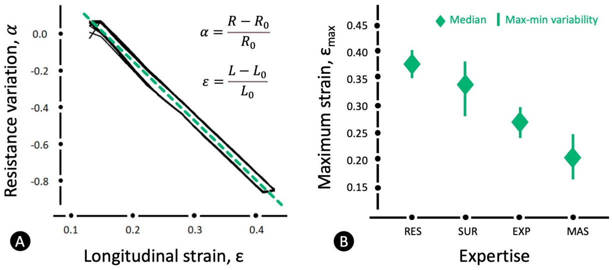

Figure 2. A) Data from uniaxial tensile test (black) and calibration curve (green). B) Proof of the *construct validity* of the simulator (expertise levels defined in the *Methods* section).

Extensive validation (on a wider population) is required to assess the real usefulness of this platform in training curricula and in different surgical specialties that involve the manipulation of vascular structures. A study on the simulator's mechanical properties is needed to properly assess its high-fidelity. Also, testing the reproducibility of the developed simulator is necessary.

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