Deformation Compensation in Robotically-Assisted Breast Biopsy*

Vincent Groenhuis[1], Eleonora Tagliabue[2], Marcel K. Welleweerd[1], Francoise J. Siepel[1], Juan D. Munoz Osorio[3], Bogdan M. Maris[2], Diego Dall'Alba[2], Uwe Zimmermann[3], Paolo Fiorini[2], and Stefano Stramigioli[1,4]

[1] Robotics and Mechatronics, University of Twente, Enschede, Netherlands
v.groenhuis@utwente.nl
[2] University of Verona, Italy
[3] KUKA Gmbh, Augsburg, Germany
[4] ITMO University, Saint Petersburg, Russia

1 Purpose

A major challenge of current breast biopsy procedures is lesion displacement due to needle-tissue interaction, respiration and involuntary motions, possibly causing the needle to miss the target. These deformations are intrinsically accounted for when the procedure is performed under ultrasound (US) guidance, but the low US resolution makes target visualization often impossible. By contrast, MRI-guided biopsies provide high-resolution images with excellent sensitivity, but they do not account in any ways for breast deformations. The MRI and Ultrasound Robotic Assisted Biopsy (MURAB) project aims to solve this challenge by the use of a combination of technologies.

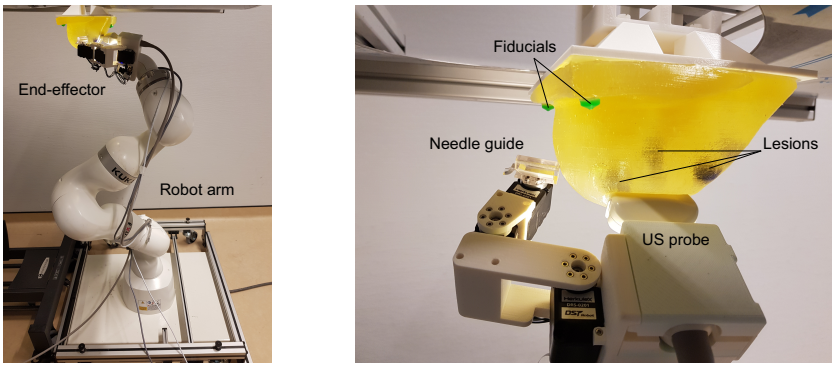

Fig. 1. Experimental setup showing phantom (with fiducials and lesions) and robot arm with end-effector consisting of ultrasound probe, stereo camera and steerable needle holder.

* This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 688188.

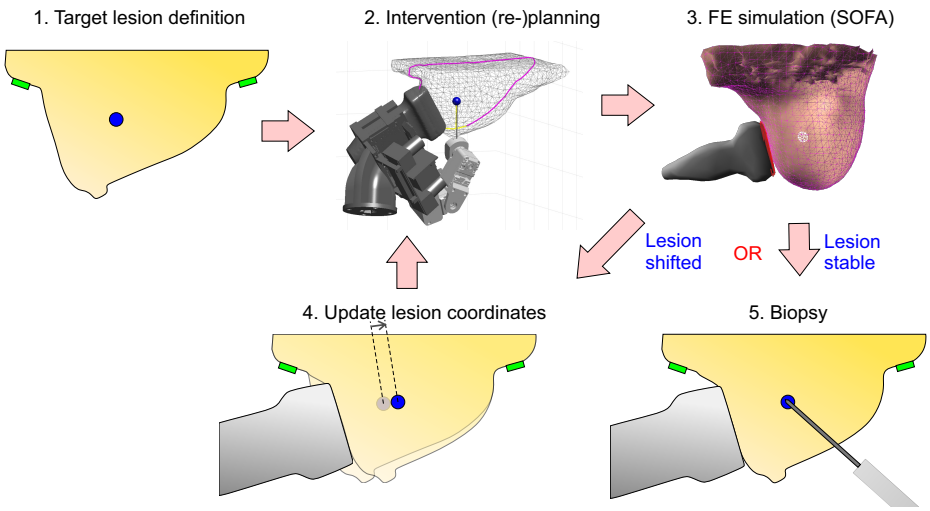

Fig. 2. Workflow in breast biopsy with deformation compensation. The target lesion is selected (1) and intervention planned (2). The intervention is simulated (3), shifting the lesion to a new location. The intervention is re-planned using this new lesion location and re-simulated using the original lesion location. Once the lesion's new location is stable the biopsy is executed (5).

A robotic arm (Fig. 1, left) outside the MRI scanner is equipped with a US probe, stereo camera with lights and a steerable needle guide (Fig. 1, right). The envisaged workflow is that the pre-operative MRI scan is co-registered with a robotically-acquired 3-D ultrasound model after which the biopsy intervention is planned taking tissue deformations induced by probe-tissue contacts into account. During the intervention, real-time 2-D ultrasound tracking is employed to perform further trajectory corrections.

The purpose of this study is to assess the feasibility of predicting lesion displacements due to probe-tissue interactions, by finite-element (FE) simulations. This is evaluated by performing a series of biopsies on a phantom under continuous contact with an ultrasound probe.

2 Methods

A soft PVC (polyvinyl chloride) plastisol phantom was created containing two stiff ink-stained lesions sized 11 mm situated 2 cm to 3 cm beneath the stiff skin surface [2]. Five green-colored PVC plastisol markers are attached to the surface, separated by rigid spacers with thickness 1.5 mm to enable automatic marker segmentation of MRI scans. The phantom has an estimated average stiffness of 4000 Pa and is mounted on a frame above the robot arm (Fig. 1).

The MRI-scanned and segmented phantom is registered to the robot coordinate frame using rigid registration of the five markers by computer vision. One

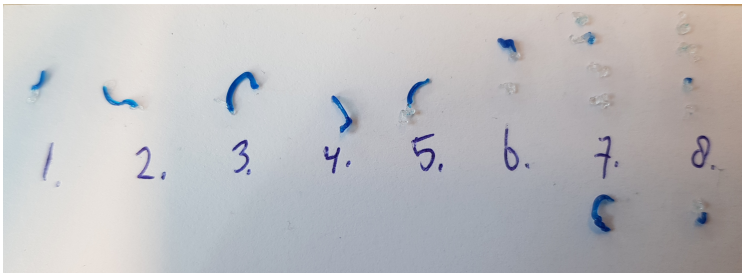

Fig. 3. Samples acquired in eight biopsies. The first five were a direct hit, the last three required two or more attempts.

of the lesions is chosen as target and the intervention procedure planned, which involves choosing a location of the ultrasound probe and the needle insertion point such that the needle trajectory is within the ultrasound plane. The probe indents the skin surface by 1 cm to 2 cm to ensure an optimal acoustic coupling, which is fundamental to be able to follow the needle on US images during the insertion.

Breast deformations induced by US probe pressure are simulated via FE method using the SOFA framework[5]. Probe-tissue interaction is modelled as a frictionless contact problem where interaction forces are computed each time as those able to satisfy the impenetrability constraint [1]. Similarly to [2], the breast is discretized with linear tetrahedra and described as a homogeneous Neo-Hookean material.

Based on the FE simulation the intervention procedure is re-planned with the updated lesion location (obtained by interpolation using FE shape functions) such that the deformation is taken into account in the new planning. This process is repeated until the simulated lesion displacement has stabilized. Figure 2 graphically summarizes the workflow.

The intervention procedure is then executed, steering the ultrasound probe and needle guide robotically to its position and inserting the biopsy needle manually through the guide to the pre-determined depth. The biopsy gun is then fired and the sample taken out. The sample is manually inspected to evaluate the extent to which it contains ink-stained matter. A biopsy is classified as a hit if the ink-stained portion of the sample is at least 2 mm in size. This process is repeated for a total of eight distinct interventions (four per lesion).

3 Results

Fig. 3 shows the samples acquired in all biopsies. The first five biopsies all resulted in a direct hit, while the last three biopsies were missed on the first attempt.

[5] www.sofa-framework.org

Three of eight biopsies, were a miss on the first attempt, indicating needle positioning errors in excess of 5.5 mm (half the diameter of the lesion). There are different possible reasons for this inaccuracy:

- The needle holder is driven by geared servo motors which are not free of backlash. The parasitic motions in the motors allow the needle to tilt over several degrees, resulting in a shifted insertion trajectory and a higher chance of missing the lesion.
- In the planning phase, we are assuming the 18-gauge (1.27 mm) needle to be rigid, following a straight path without deforming tissue. This assumption may not hold in real scenarios, where needles (especially with a beveled tip) can actually bend during insertion and also cause additional deformations.
- Modelling breast-probe interaction as a frictionless problem allows probe sliding motion in some cases. However, in our setup, the contact surface remains constant. Accounting for frictional effects might help to reflect the actual behavior.
- Registration errors in visual marker detection and registration also contribute to targeting errors. In rigid registration of the five fiducials the mean error was measured to be approximately 2 mm.

4 Conclusion

The study has shown that it is possible to effectively compensate for deformations using FE simulations within the MURAB workflow. Not all biopsies were a direct hit, indicating errors in excess of 5.5 mm. Several aspects such as component calibration, needle guide actuation, needle depth guiding system, FE simulation accuracy and phantom registration need to be investigated and improved where possible, in order to obtain an acceptable success rate in the breast biopsy procedure. With these factors taken into account, MURAB may be a promising system for performing breast biopsies in the future.

References

1. Duriez, C., Andriot, C., Kheddar, A.: Signorini's contact model for deformable objects in haptic simulations. In: Intelligent Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on. vol. 4, pp. 3232–3237. IEEE (2004)
2. Visentin, F., Groenhuis, V., Maris, B., Dall'Alba, D., Siepel, F., Stramigioli, S., Fiorini, P.: Iterative simulations to estimate the elastic properties from a series of mri images followed by mri-us validation. Medical & biological engineering & computing pp. 1–12 (2018)