Initial study of breast tissue retraction toward image guided breast surgery

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ABSTRACT

Image-guided surgery may reduce the re-excision rate in breast-conserving tumor-resection surgery, but image guidance is difficult since the breast undergoes significant deformation during the procedure. In addition, any imaging performed preoperatively is usually conducted in a very different presentation to that in surgery. Biomechanical models combined with low-cost ultrasound imaging and laser range scanning may provide an inexpensive way to provide intraoperative guidance information while also compensating for soft tissue deformations that occur during breast-conserving surgery. One major cause of deformation occurs after an incision into the tissue is made and the skin flap is pulled back with the use of retractors. Since the next step in the surgery would be to start building a surgical plane around the tumor to remove cancerous tissue, in an image-guidance environment, it would be necessary to have a model that corrects for the deformation caused by the surgeon to properly guide the application of resection tools. In this preliminary study, two anthropomorphic breast phantoms were made, and retractions were performed on both with improvised retractors. One phantom underwent a deeper retraction that the other. A laser range scanner (LRS) was used to monitor phantom tissue change before and after retraction. The surface data acquired with the LRS and retractors were then used to drive the solution of a finite element model. The results indicate an encouraging level of agreement between model predictions and data. The surface target error for the phantom with the deep retraction was 2.2 +/- 1.2 mm (n=47 targets) with the average deformation of the surface targets at 4.2 +/- 1.6mm. For the phantom with the shallow retraction, the surface target error was 2.1 +/- 1.0 mm (n=70 targets) with the average deformation of the surface targets at 4.0 +/- 2.0 mm.

1. INTRODUCTION

Breast cancer has become the most frequently diagnosed cancer in the world among females [1], and with this increase in detection has come an increase in breast-conserving surgery as a treatment option. Surgical resection remains the primary treatment for breast cancer. However, unnecessarily large amounts of tissue may be removed due to the fact that the surgeon may be unsure of where the tumor margins are located. In addition, re-excision is often necessary in many breast surgeries due to positive margins in the removed tissue [2], [3]. Indeed, the study by [3] has shown that there is a significant increase in the local recurrence of breast cancer in the cases where there is a persistent positive margin when compared with cases where a negative margin was achieved. A negative margin resection is essential to a successful lumpectomy while positive margins are considered a contraindication [4]. Reoperation is required in 17-59% of cases to obtain a negative margin resection [5].

Fig. 1: Deformation observed in surgery as reproduced from [7].

If the location of the tumor were known from imaging studies, the use of image guided surgery techniques could provide a more accurate way for the surgeon to obtain adequate margins with minimal loss of tissue without the use of guide wires or other means of tumor localization. Intraoperative margin assessment has been shown to cause a significant decrease in reoperations as well as a decrease in total operative costs [6], and this along with image guidance may decrease these numbers further while also leading to quicker surgeries with less volume lost.

However, there are two main challenges to overcome to use image-guidance in breast-conserving tumor-resection surgery: (1) preoperative diagnostic images (MR, CT, and/or mammography) are acquired in significantly different orientations than their surgical presentation counterpart, and (2) breast surgery is a dynamic process with a great deal of deformation occurring during its execution, as in Fig. 1 [7]. One possible solution is to use tracked intraoperative ultrasound imaging and/or laser range scanning coupled to deformation correction methods.

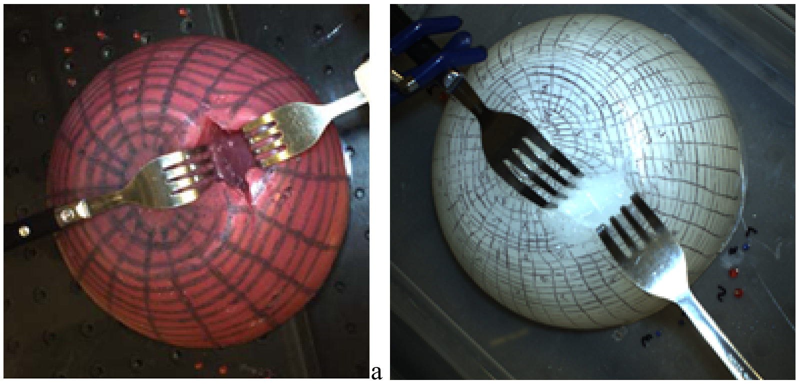
With respect to intraoperative deformation, a major source of deformation occurs when the surgeon positions the breast for a suitable entry point and uses retractors to open the site for tissue removal. Accounting for this source of deformation will be essential to providing useful subsurface shift correction for image guidance. Modeling of this surgical event can provide useful deformation correction insight towards the feasibility of image guidance in breast surgery. In this paper, we are investigating a relatively inexpensive way to correct for these deformations using biomechanical models.

2. METHODS

In this work, we acquired surface data of two anthropomorphic breast phantoms pre- and post- resection using a laser range scanner (LRS). The data from the LRS is a textured point cloud; i.e. it captures the geometric shape of the object of interest but also maps the color of the field of view as captured from a standard digital color camera onto the point cloud. The first breast phantom was created using a silicone, tissue mimicking material ("Ecoflex 00-10," Smooth-On, Inc., Easton, PA) while the second was made from polyvinyl alcohol.

A cross-hatch pattern was drawn on both so that measurements of the surface displacement could be acquired with the LRS. A CT scan was taken prior to the retraction experiment, and this was used to construct a finite element computer model for both phantoms. The CT volumes were segmented using AnalyzeAVW (Biomedical Imaging Resource; Mayo Foundation, Rochester, MN), and a surface was made using the marching cubes algorithm [8]. From the surface, a finite element elastic model with homogeneous mechanical properties was generated to simulate intraoperative deformations. The LRS surface data that was acquired was registered to the segmented CT surface using a variation of the iterative-closest point method.

A retraction was then performed on both phantoms with the first phantom having a deep retraction (Fig. 2a) and the other phantom having a shallower retraction (Fig. 2b). Deformations were achieved that were comparable to a real surgical resection (Fig. 1) as described in [7]. A second LRS was taken of the deformed



a b

Fig. 2: (a) A retraction was performed on a breast phantom with a deep tissue retraction, and (b) a retraction was performed with a more shallow retraction, both with comparable deformation to that achieved in a surgical setting, as in Fig. 1.

phantoms so that surface displacements could be measured (n=47 points for the phantom with the deeper retraction and n=70 points for the phantom with the shallower retraction). Radial basis functions (RBF) were created from the two LRS point clouds that were registered to their respective CT surfaces (Fig. 3). The measurements encompassed the location of the hatching cross-points surrounding the retractors. The FastRBF toolkit (Christchurch, NZ) fit a surface to the LRS point cloud while also eliminating spurious points. Point correspondences between the undeformed and deformed phantoms were made by using the surface markings on the phantom. Using the markings on the phantom, we selected corresponding points on the 2D LRS bitmaps before and after retraction. A sample post retraction LRS bitmap is shown in Fig. 2. The corresponding 3D point was found on the LRS point cloud using the FastRBF toolkit. The incision site was digitized by using a Polaris optical tracking system. By using this system with a tracked stylus, the points along the site of incision could be marked with the stylus. This allowed the creation of a plane to approximate the depth of the retraction. Using the digitized points, the virtual "retractor" plane could be inserted into the volumetric mesh. The volumetric mesh was split along the plane to simulate the retraction.

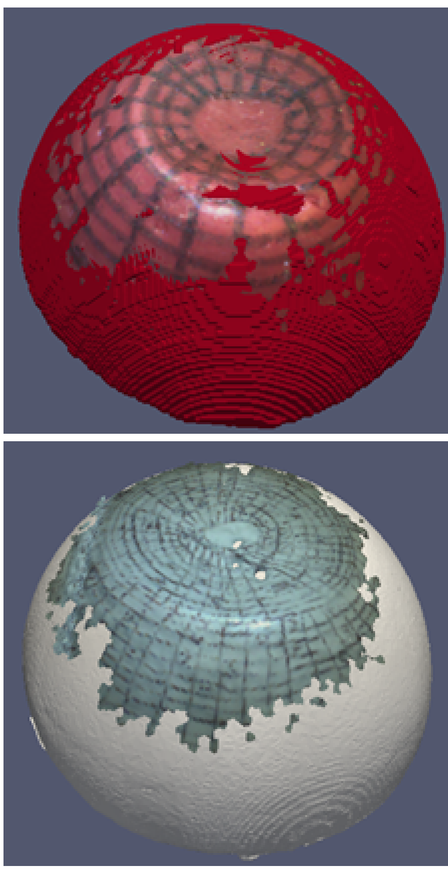


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Fig. 3: Registered RBFs with CT surfaces. Markings on RBF surface allowed for point correspondence between the pre- and post-retracted phantom.

By digitizing the points of the retractor pre- and post-retraction, appropriate boundary conditions could be found for the mesh. In the simulations for both phantoms, the surrounding points on the texture were used as simulated surface targets to assess model predictive error. The measurements surrounding the retractor were made by tracking corresponding points between the undeformed and deformed phantom. This allowed for the determination of the actual surface displacement achieved by the markings on the surface of the phantom. In addition, registering both of the phantom LRS-acquired RBFs with their respective CT surfaces allowed the localization of pre-deformed markers on the volumetric mesh for each phantom which also includes the localization of the retractor and the incision. Once completed, the measurements could be applied to a linear elastic finite element model of the phantom to simulate motion. Boundary conditions reflected the retraction, stress free outside the retraction area, and a fixed base.

3. RESULTS

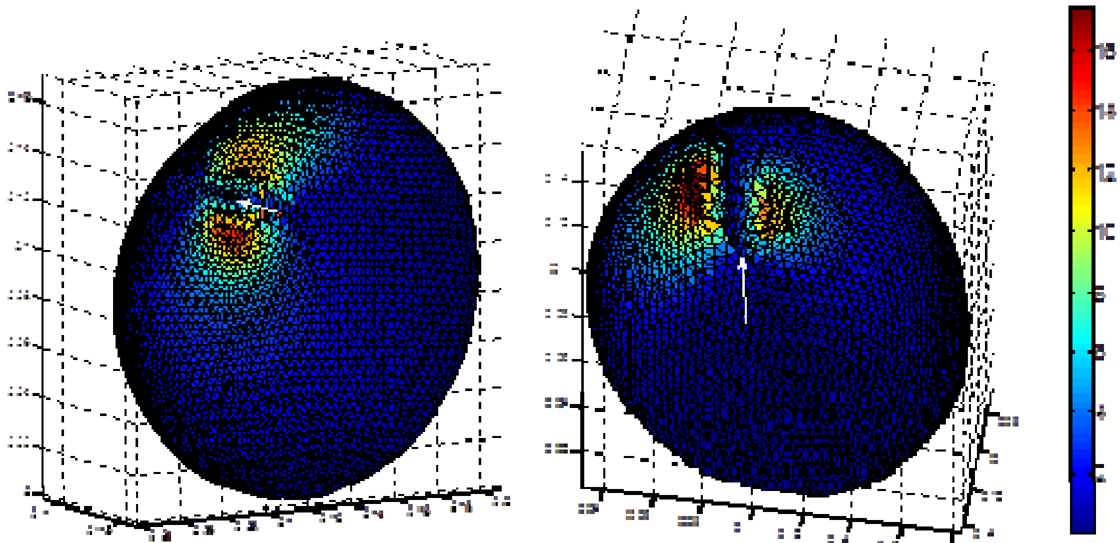

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Fig. 4: Total simulated displacement for mesh: (a) deeper and (b) shallower retraction. Color scale is in millimeters. Arrows are pointing at mesh opening.

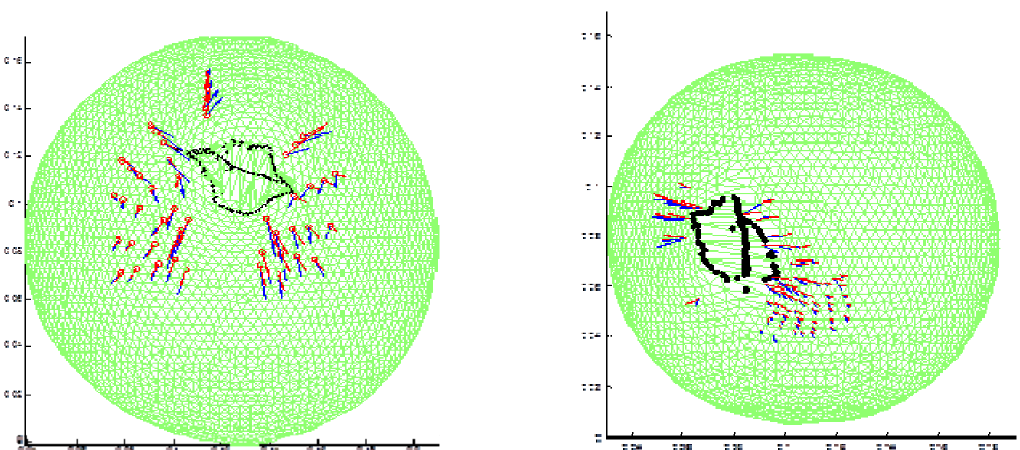

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Fig. 5: Frontal view of phantom models with deep (a) and shallow (b) retractions with deformed mesh based on retractor boundary conditions. Blue and red vectors represent measured and predicted movements respectively. The cavity is marked with black dots. The row of black dots transecting the cavity are the retractors' initial entrance.

Fig. 4 represents the total simulated displacement of the deformed mesh using boundary conditions for a deeper retraction (Fig. 4a) and using boundary conditions to represent a shallow retraction (Fig. 4b). Fig. 5 illustrates the overlay of the results from both retraction simulations on the phantoms with the deeper (Fig. 5 a) and shallower (Fig. 5 b) retractions compared to their measured counterparts. The measured and predicted displacement vectors are shown in Fig. 5 also, which shows the relative accuracy that the simulation achieved in predicting the displacement along the surface of the phantoms. Overall we see considerable agreement for both simulations.

The opening of the mesh created by the simulated retraction in both cases matches the measured opening of the physical retraction very well. Using the markings on the phantoms as targets, the target error was 2.2 +/- 1.2 mm and 2.1 +/- 1.0 mm for the phantoms with deep and shallow retractions respectively. The average deformation of the surface targets was 4.2 +/- 1.6 mm and 4.0 +/- 2.0 mm for the phantoms with the deeper and shallower retractions respectively.

4. DISCUSSION

With respect to the application of the retractors, our experiment is based on a relatively crude tracking framework for the application retractor trajectory. Undoubtedly there are subtle aspects to tissue correspondence during retraction that were somewhat compromised in this experiment. Nevertheless, we do see considerable agreement between the predicted and observed displacements of the targets on the surface of the phantoms. Furthermore, these initial results are encouraging with an approximately 50% rate of deformation correction for both phantoms.

5. CONCLUSION

Within the breast cancer surgery community, the goal of breast preserving surgery is an important outcome. The level of re- resection during surgery as a result of pathological margin reports as well as the need for reoperation due to recurrence is a pressing problem and one that surgical guidance may play an important role. As most surgeries are performed in a significantly different orientation than preoperative imaging modalities, intraoperative imaging such as ultrasound and laser range scanning coupled to deformation compensation methods to translate image-guidance technology would be an important development. Retraction during breast surgery is a dynamic process. This paper begins to look at the power that computational models have in predicting these surgical conditions.

The results here are preliminary and represent a first attempt at generating a realistic anthropomorphic phantom with realistic simulated breast retraction. The model calculations that have been performed are encouraging with approximately a 50% deformation correction rate in both phantoms. Some ways that the accuracy of the simulation can be improved is by using a nonlinear model instead of a linear one. Using the displacement of the surface markers as boundary conditions will also improve accuracy once we start tracking the deformation of subsurface targets. The future direction for this work will be to add subsurface targets to the phantom to see the accuracy of the model in predicting the subsurface deformations.

6. REFERENCES

[1] Jemal, A., Bray, F., Center, M. M., Ferlay, J., Ward, E., and Forman, D., "Global cancer statistics", CA: A Cancer Journal for Clinicians 61(2), 69-90 (2011).
[2] Carter, T. J., Tanner, C., Crum, W. R., Beechey-Newman, N., Hawkes, D. J., "A framework for image-guided breast surgery", Medical Imaging and Augmented Reality 4091, 203-210 (2006).
[3] Singletary, S. E., "Surgical margins in patients with early-stage breast cancer treated with breast conservation therapy", American Journal of Surgery 184(5), 383-393 (2002).
[4] N. C. C. Network, "NCCN Clinical Practice Guidelines in Oncology: Breast Cancer," (2011).
[5] Park, C. C., Mitsumori, M., Nixon, A., Recht, A., Connolly, J., Gelman, R., Silver, B., Hetelekidis, S., Abner, A., Harris, J. R., and Schnitt, S. J., "Outcome at 8 years after breast-conserving surgery and radiation therapy for invasive breast cancer: Influence of margin status and systemic therapy on local recurrence", Journal of Clinical Oncology, vol. 18, pp. 1668-1675 (2000).
[6] Uecker, J. M., Bui, E. H., Foulkrod, K. H., Sabra, J. P., "Intraoperative assessment of breast cancer specimens decreases cost and number of reoperations", American Surgeon 77(3), 342-344 (2011).

[7] Haid, A., Knauer, M., Dunzinger, S., Jasarevic, Z., Koberle-Wuhrer, R., "Intra-operative Sonography: A valuable aid during breast-conserving surgery for occult breast cancer", Annals of Surgical Oncology 14(11), 3090-3101 (2007).
[8] Lorensen, W. E. and Cline, H. E., "Marching cubes: A high resolution 3D surface construction algorithm", Int. Conf. Comput. Graphics Interactive Tech. (SIGGRAPH) Comput. Graph 21(4), 163-169 (1987).