Characterization of a Phantom Setup for Breast Conserving Cancer Surgery

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ABSTRACT

The purpose of this work is to develop an anatomically and mechanically representative breast phantom for the validation of breast conserving surgical therapies, specifically, in this case, image guided surgeries. Using three patients scheduled for lumpectomy and four healthy volunteers in mock surgical presentations, the magnitude, direction, and location of breast deformations was analyzed. A phantom setup was then designed to approximate such deformations in a mock surgical environment. Specifically, commercially available and custom-built polyvinyl alcohol (PVA) phantoms were used to mimic breast tissue during surgery. A custom designed deformation apparatus was then created to reproduce deformations seen in typical clinical setups of the pre- and intra-operative breast geometry. Quantitative analysis of the human subjects yielded a positive correlation between breast volume and amount of breast deformation. Phantom results reflected similar behavior with the custom-built PVA phantom outperforming the commercial phantom.

Keywords: breast cancer, lumpectomy, registration, breast conservation therapy, finite elements, biomechanics, modeling

1. INTRODUCTION

Treatment for early stage breast cancer usually involves a lumpectomy and radiation treatment, together known as breast conservation therapy (BCT). BCT has the risk of reoperation due to difficulty in determining tumor borders intraoperatively. A comprehensive framework for image-guided breast surgery using supine magnetic resonance (MR) images, patient specific biomechanical models, and intraoperative ultrasound has been proposed [1, 2] as a superior intraoperative tumor localization strategy. A mock surgical setup that could be used to evaluate data acquisition and registration methods for such surgical systems would be of great value. Therefore, in this study, a phantom setup with realistic breast geometry and elasticity is described along with a custom deformation apparatus designed to reproduce breast tissue deformation seen between preoperative images of the breast and the intraoperative configuration of the breast.

The preoperative state within the imaging unit is associated with the subject in the supine position with the ipsilateral arm placed above her head. The intraoperative state involves the subject in the supine position with the ipsilateral arm placed out approximately perpendicular from the body. The breast deforms considerably between the two states. Ebrahimi et al. report the tumor center of mass difference between two supine setups in [3]; one with the arm parallel to the body, and one with the arm above the patients head. The center of mass difference of the tumor between these

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\two arm positions averaged 2.78 cm and ranged between 1 and 4.6 cm. This study indicates that significant deformation occurs due to differences in ipsilateral arm placement. The motivation for the work presented here is that in order to properly validate non-rigid correction algorithms and image guidance techniques, there is a need to take quantitative measurements in a controlled manner. Furthermore, individual differences in the clinical setting limit reproducibility, which is an issue that can be remedied by the use of a phantom. Commercial breast phantoms are available, such as the Breast Probe (SIMULAB Corporation, Seattle, WA) and the Complex Breast Phantom (SynDaver Labs, Tampa, FL), and while they do represent surface anatomy, they do not represent physiologic elasticities and deformation characteristics.

2. METHODS

2.1 Analysis of Clinical Breast Deformation

Breast deformations that occur clinically from the preoperative state to the intraoperative state were characterized by analyzing deformations seen in three patients scheduled for a lumpectomy and in four healthy volunteers in mock surgical setups. The data from patients and healthy subjects were acquired under an Institutional Review Board (IRB) approved study. In the fourth volunteer, MR images and mock intraoperative data was acquired for both breasts, yielding seven total data sets. The magnitude and direction of breast surface deformation was measured using MR-visible fiducial markers, as seen in Figure 1 (IZI Medical Products, Owing Mills, MD). MR images of the breast in the supine configuration were acquired using a 16-channel sensitivity encoding (SENSE) torso coil. The coil was situated as to not apply any unnatural deformations to the breast. High resolution anatomical images were acquired using a T1-weighted sequence with fat suppression. Fiducial center points in the MR images were manually determined. In the mock surgical setup, the geometric coordinates of the synthetic surface fiducials were acquired using an optically tracked stylus and NDI Polaris Spectra (Northern Digital, Waterloo, ON, Canada). The fiducial markers were used to calculate fiducial registration error (FRE), a measure of overall landmark misalignment, and an intrafiducial (IF) distance distribution, used to determine both magnitude and direction of clinical deformation. The differences in FRE & IF distance distribution between the two positions were reported to establish a non-rigid surface deformation characterization. Breast volume for each subject was also determined by semi-automatic segmentation of the breast tissue.

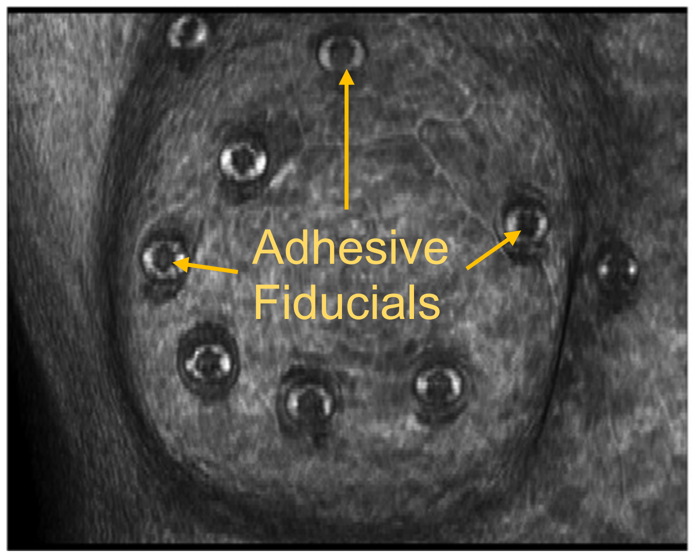


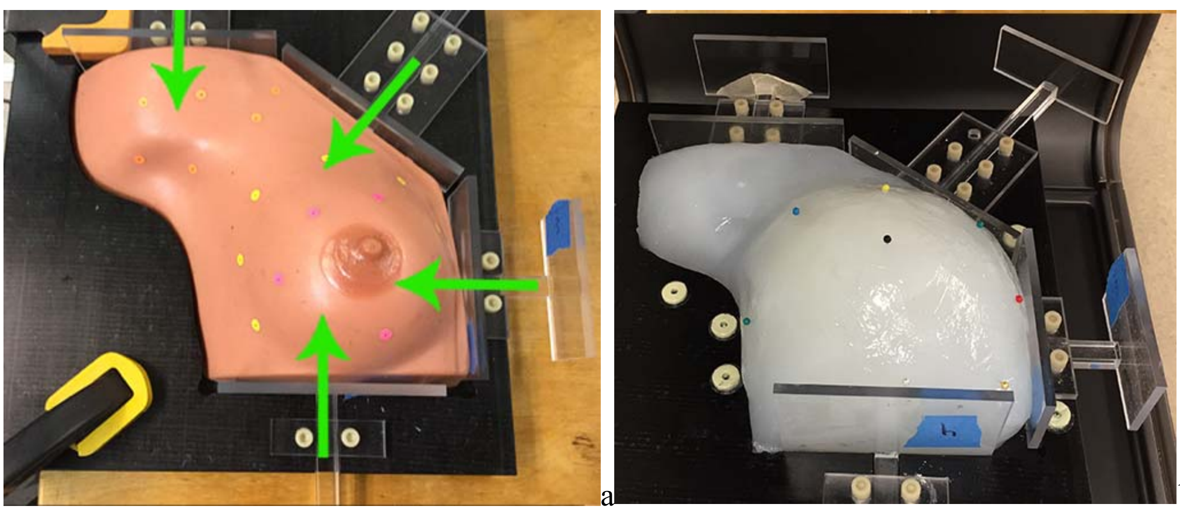
Figure 1. Volume render of breast in supine position with synthetic, MR-visible fiducial markers

The differences in intrafiducial distances between the preoperative imaging environment and intraoperative configuration represent the magnitude of non-rigid deformation occurring between the two states. A covariance matrix of these values was computed, and used to find the principle axes of deformation by solving for the eigenvalues and eigenvectors. These eigenvectors provide a quantitative representation of the anatomically-relevant directions of principle deformation associated between the two presentation states. By registering all physical space fiducials in the surgical presentation to the MR counterparts, trends among the principal directions can be compared and correlated to standard anatomical directions due to the uniformity of MR patient imaging.

2.2 Phantom Design

Poly(vinyl) alcohol (PVA), a synthetic polymer commonly used for approximating soft tissue [4], was used to simulate breast tissue. The phantoms were developed with the ability to include features such as elastically-representative fibroglandular tissue and tumors. This setup has been used previously in breast phantoms used for sonographic validation within microwave imaging systems [5]. However, the phantoms presented here are able to be used without a shell encasement, a limitation commonly associated with many existing phantoms for sonographic use [6-8]. This makes the setup well-suited for validation of intraoperative surgical guidance methods and tomographic imaging, regardless of whether the phantoms are used in the supine or pendant position. We should also note that the phantoms presented here closely resemble surface anatomy, mimicking not only the shape of the breast itself, but the surrounding tissue ipsilateral arm region as well.

2.2.1 Phantom Preparation



a b

Figure 2. (a) SimuLab Breast Probe, and (b) PVA phantom in deformation apparatus. Green lines illustrate directions compression can be applied to phantom

The mold for the breast phantom was similar to the one shown in Figure 2a which is the Breast Probe phantom from SIMULAB Corporation (Seattle, WA). The phantom mold was coated with small beads for tracking. These beads became embedded in the surface of the phantom upon freezing. Beads were used because adhesive fiducial markers do not adhere well to the phantom surface. Each phantom was prepared by combining water and 7% by mass of (poly)vinyl-alcohol (Sigma Aldrich 341584), which was then heated to 80 degrees C. 10% by volume of glycerin was added (Sigma Aldrich G7893), then placed on a stirring stand until significantly cooled (this cooling is not explicitly necessary, but assisted in keeping beads in place while pouring). The solution was carefully poured into the molds and left uncovered in the freezer for at least 14 hours, then thawed for another 14 hours. It was discovered that leaving the phantoms uncovered in the mold is crucial to achieving the proper stiffness, due to the rate the phantoms dry while freezing/thawing.

2.2.2 Deformation Apparatus

A deformation apparatus was created with four manipulators able to induce and hold compressive forces on the breast (Figure 2). All four manipulators can be deployed at once, individually, or in some unique configuration. The base of the deformation frame contains a 1 cm depression machined to have the same contour as the breast phantom mold. This allows the breast phantom to sit flush in the base and hold applied deformations while minimizing slip. It should be noted that the deformation apparatus only provides compressional forces on the phantom; however, the clinical deformation can still be reproduced, based on the results from the principle component analysis which showed that primary deformation occurs along the patient's superior-inferior axis, and secondary deformation occurring along the medial-lateral axis.

2.3 Measuring Phantom Deformation

Two phantom materials were compared in this phantom setup. The first material was a commercially available breast phantom with realistic synthetic tissue (SIMULAB Corporation, Seattle, WA – Figure 2a). The second analysis was done using the PVA gel described above. Each phantom was placed in the deformation base and markers were dispersed on each surface. Surface markers were digitized for the baseline (undeformed) and deformed state using an optically tracked stylus. FRE and IF distance distribution differences were calculated for each phantom and compared to the clinical data sets.

3. RESULTS

3.1 Clinical Breast Deformation

Analysis of non-rigid deformation between the supine MR images and mock intraoperative breast configuration yielded a positive correlation between breast volume and the amount of deformation. The fiducial registration error (FRE), was calculated for all cases. FRE indirectly captures an estimate of non-rigid changes by looking at changes with respect to breast volume. The assumption is that fiducial localization error (FLE) is similar among women with different breast volumes but that soft tissue changes due to arm motion would be exacerbated with larger breast women. More specifically, the effects of chest wall attachments would inhibit deformation effects in smaller breast women. Figure 3a is a graph showing the correlation between breast volume and FRE for the 7 human subjects. The correlation coefficient between volume and FRE is 0.93. Figure 3b shows the maximum IF distance distribution difference between preoperative and intraoperative states also as a function of subject breast volume.

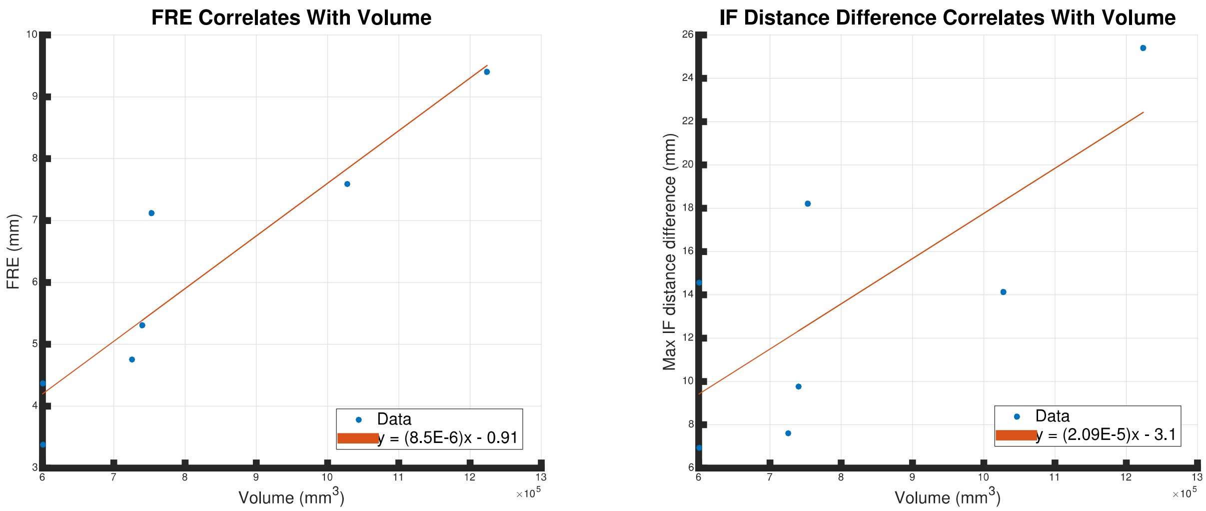


Figure 3. The relationship between breast volume and (a) fiducial registration error, and (b) and maximum intrafiducial distance differences associated with the tracked adhesive fiducial markers distributed on the breast surface.

While not as strong a correlation as FRE, the maximum IF distance distribution difference correlated with volume with a 0.74 correlation coefficient. Across the subject population the FRE average, and maximum IF average was 6.0 ± 2.1 mm, and 13.8 ± 6.5 mm, respectively. Also of note, in a qualitative comparison of the maximum IF distance distribution differences, most deformation occurred along the subjects' inferior-superior axis, with minor deformations occurring along the subjects' medial-lateral axis.

The principle component analysis performed on the seven human cases confirmed this quantitatively. Figure 4 shows the three principle components of deformation for each case with the average also shown. Analyzing the breast fiducials from the supine MR preoperative state to the supine intraoperative state, the largest motion is approximately in the superior-inferior direction, and the second largest is approximately in the medial-lateral direction. Based on the PCA analysis, the motion in the superior-inferior direction is approximately 2.3 times greater than medial-lateral motion, and 6.2 times greater than anterior-posterior motion on average.

3.2 Phantom Deformation

Each phantom (Breast Probe, and our molded PVA-gel) had a volume of 7.2×10^5 mm^3. The FRE between mock preoperative and intraoperative states for the commercial phantom and PVA gel phantom was 3.8 mm, and 5.05 mm, respectively. When comparing that to the clinical results of Figure 3a, the FRE value for the PVA phantom more closely matched the expected value for this breast volume (5.2 mm in Figure 3a) than the commercial phantom. The maximum IF distance distribution difference between mock preoperative and intraoperative states for the commercial and PVA gel phantom was 8.31 mm, and 13.28 mm, respectively. When comparing to Figure 3b, the PVA gel phantom provided deformations closer to those seen clinically (11.95 mm in Figure 3b).

4. DISCUSSION

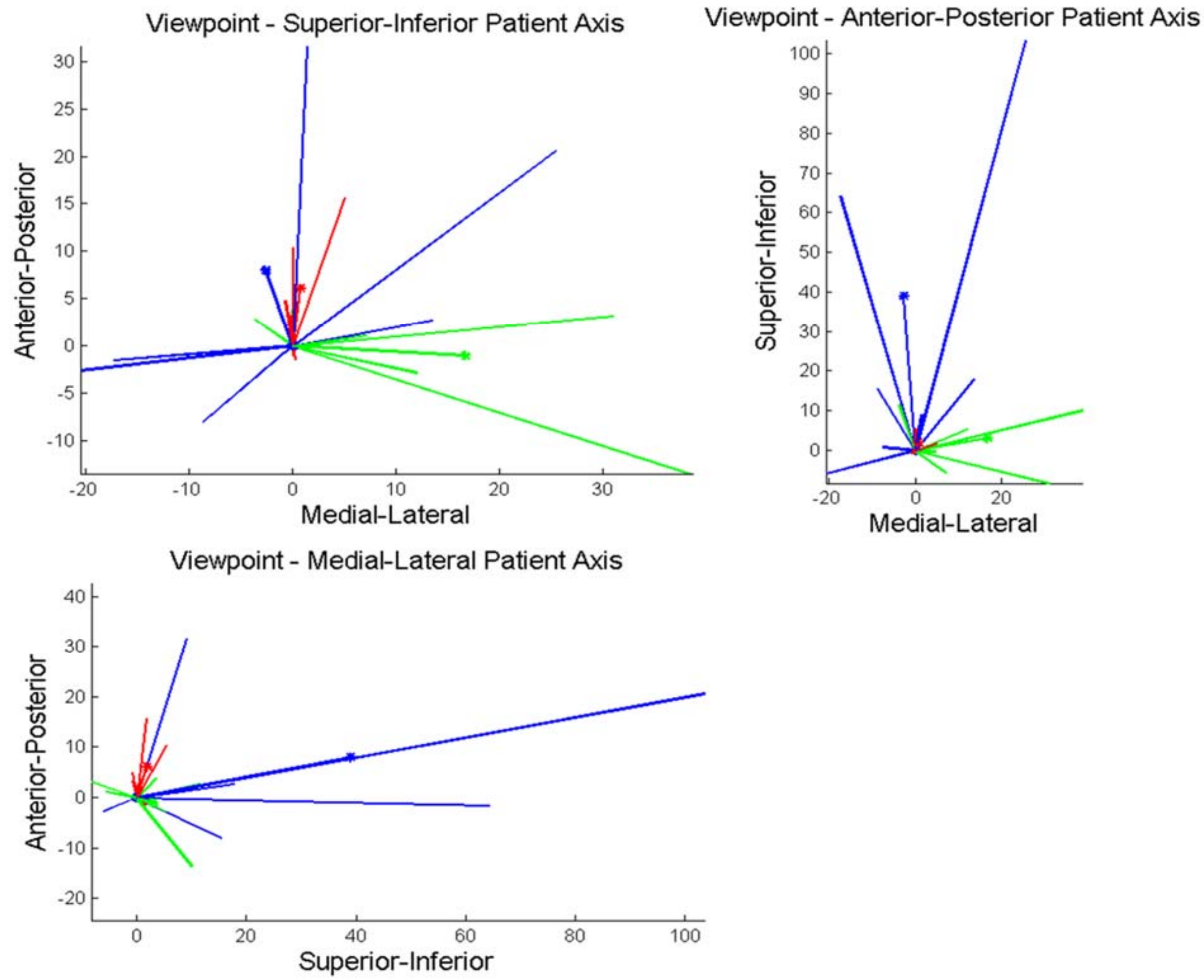


Figure 4. Results from principle component analysis of breast deformations reveal primary (blue lines), secondary (green lines), and tertiary (red lines) principle components for each of 7 cases. The asterisk designated lines represent the average principal component directions over all 7 cases. Note, vector magnitudes are expressed in voxels.

The clinical deformation analysis was used to characterize the directions and magnitude of deformation between the supine MR imaging environment and the supine intraoperative state. This analysis was then used as a guideline to develop the phantom and fine tune its material properties. It should be noted that supine MR imaging was used for its more accurate representation of the breast during the lumpectomy procedure [1]. As noted earlier, the deformation apparatus applies compressional forces on the phantom. While this force does not mimic the physiological counterpart with respect to the deformation, it does embody the effects of those sources of deformation in terms of magnitude, direction, and location of movement between the two states.

5. CONCLUSIONS

In this study, we quantitatively analyzed breast surface deformation between preoperative and intraoperative breast states using breast cancer patients and healthy volunteers in the supine imaging-to-intraoperative positioning. Using this analysis, we designed a breast-mimicking phantom capable of realistic breast deformation as a way to test and validate platforms for image guided breast surgery. The representative PVA breast phantom was shown to be a viable option for the use in evaluating image guidance systems for breast surgery.

6. ACKNOWLEDGEMENTS

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