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In-vivo quantification of human breast deformation associated with the position change from supine to upright

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Abstract

Stereophotographic imaging and digital image correlation are used to determine the variation of breast skin deformation as the subject orientation is altered from supine to upright. A change in subject's position from supine to upright can result in significant stretches in some parts of the breast skin. The maximum of the major principal stretch ratio of the skin is different in different subjects and varies in the range of 1.25–1.60. It is also found that the boundaries of the breast move significantly relative to the skeletal structure and other fixed points such as the sternal notch. Such measurements are crucial since they provide basic data for validation of biomechanical breast models based on finite element formulations.

Keywords

Biomechanics; Image correlation; Deformation measurement

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1. Introduction

Breast cancer is a leading cause of noncutaneous cancer among American women, with up to one in eight women expected to develop breast cancer within their lifetime [1]. To enhance restoration of the physical appearance of the breasts and the patient's quality of life, satisfaction, and body image, mastectomy is often followed by a breast reconstruction. In order to aid patients and surgeons in the decision making procedure for the different types of reconstructions, it is useful to develop a patient-specific three-dimensional (3D) mechanistic finite-element (FE) model with realistic initial geometry of the breast, boundary conditions, and well-calibrated material constitutive models.

Predictive breast biomechanical models have been under investigation for different purposes. Some are intended to correlate the results of different diagnostic medical procedures such as MRI, X-ray, and biopsy [2–5] where the prevailing deformation during imaging is compression while others [6–9] have been developed with the aim of investigating the changes in the shape of the breast that occur due to a change in gravity load caused by a change in position, for example, from prone or supine to upright. Material characterization and development of 3D finite element models capable of predicting this shape change from available medical images have been the immediate goals of these studies, with the eventual goal of simulating breast shape changes after surgical reconstructions. Our group is involved in the development of a physics-based biomechanical model of the breast.

Physics-based models are constructed as follows: the shape of the breast is identified by 3D stereophotography surface imaging; the skin is considered to be a deformable material, and modeled as a hyperelastic material [7–10]. The back surface of the breast is defined by the surface of the chest wall and its geometry is some-times obtained through MRI. The breast volume between the skin and the chest wall is considered to be filled with another hyper-elastic material. While it is recognized that the skin is anisotropic and subjected to an unknown prestretch, with both of these varying with position on the breast, it is difficult to quantify these effects accurately. Simplified version of anisotropy or even isotropy of skin is typically imposed in biomechanical models of the breast. Also, the stress-free reference configuration is taken to correspond to the geometry obtained either in the supine position [8] or the prone position when immersed in water as a neutrally buoyant environment [7].

Validation is the most critical step in the development of these FE models; typically, only the shapes of the breast are compared through registration procedures [9]. In the literature, the breast skin is considered to play a minor role in supporting the weight of the breast; it is thought that Cooper's ligaments and other connective tissues of the breast and chest wall play a bigger role in supporting the weight. However, if the skin plays even a minor role in supporting the breast, then it can be expected that the stretch of the skin would change with orientation of the subject relative to gravity. An ideal biomechanical model should not only predict the correct shape of the breast, but also should yield the state of stretch on the breast skin (deformation). While registration techniques based on projected distance measures can determine the difference between two shapes, they are not capable of comparing the actual measurable stretch on the breast skin and the predicted values from a FE model.

del Palomar et al. [8] appear to be the first to have made an effort to measure the skin deformation; they accomplished the measurements by marking six line segments on one breast and then measuring (apparently manually) the changes in the lengths of these line segments with the patient in the upright and supine positions. Only three of the six segments exhibited length changes since they were on the deforming part of the breast surface. The other segments did not stretch because they were placed along the sternum, just below the clavicle, and below the inframammary fold, respectively. Their emphasis was on calibrating material properties of the skin, fat and fibroglandular tissues rather than in exploring the inherent stretch variations on the breast surface. Large rotations of line segments that occur during shape changes, as can be verified from images corresponding to supine and upright positions, were not addressed. Complete shape matching requires consideration of the large rotations as well as the varying stretch at different parts of the breast.

As a prelude to the construction of a complete biomechanical model of the breast, we explore the position of the breast relative to the skeletal structure and the skin deformation of the native and surgically altered breast for five female subjects. This was accomplished by comparing the changes in the shape and deformation of the breast in supine, upright and other intermediate positions; in concert with this the skin undergoes large deformations. A manual implementation of three-dimensional digital image correlation (3D-DIC) was used to obtain the 3D displacement vectors and consequently the in-plane stretches and rotations of the skin at a large number of points on the breast with the subject tilted in different positions, i.e., 45°, 60° and upright or 90° relative to the supine or 0° position. These measurements provide a reliable way to monitor breast position relative to the musculoskeletal structures and the deformation of the skin of the breast and the skin overlying the skeletal structures, and hence a method to determine the mechanical properties of the skin. Specifically, the following are examined:

- (i) The distributions of stretch and rotation on the breast skin are measured. This facilitates the formulation and validation of biomechanical models of the breast.
- (ii) The biaxiality of the deformation in the breast is examined considering isotropic and anisotropic material response.
- (iii) The position changes of the subject's breast relative to fixed points on the skeleton are determined. The sternal notch is identified in each orientation by the surface curvature in this region; the movement of the skin relative to this point is identified.

2. Methods

In order to quantify the shape change and deformation of the breast skin associated with change in orientation of the body, the surface of the breast was first marked¹ with a pattern of radial lines emanating from the nipple, a set of circles nearly concentric with the areola, and a random pattern of dots, dashes, and lines; we will refer to these as Lagrangian marker points since they identify the material points in the image; between 150 and 650 distinct

¹Surgical marker pen was used to make these patterns

points were identified in each 3D image set for 3D-DIC analysis. Second, 3D stereophotography surface imaging system,² mounted on a tilt table³ was used to capture images of the marked breasts with the subject tilted to 0° (supine), 30°, 45°, 60° and 90° (upright); details of this tilt-table system are described elsewhere [11]. With this system, we are able to acquire full three-dimensional shape and deformation information of most of the breast's surface at each orientation of the tilt table, in the form of a 3D point-cloud representation of the surface of the breast as well as a texture map that contains the light intensity information. Even with the current advanced system with four cameras, there are cases when some parts of the breast surface may not be fully captured due to occlusion of parts of the surface from the view field of the cameras. Third, a manual 3D-DIC scheme was used to determine correlating points in the breast images corresponding to different orientations. Because fully automated 3D-DIC systems to determine the deformation of the breast skin over the entire breast surface are not available, identification of the Lagrangian marker points was accomplished manually; each image was viewed at high magnification, and the coordinates of the dots, dashes and line crossings of the patterns marked on the breast were acquired digitally. Since the spatial resolution of the original point-cloud was 1 mm, the point-cloud density was increased by performing a surface subdivision procedure followed by a Poisson-disk resampling technique, which was implemented to obtain an equally spaced point-cloud with the resolution of approximately 0.1 mm. This step, which was performed using a freeware called MeshLab [12], decreases the error in point selection step substantially.

Finally, there are different methods to estimate the breast volume [13,14]. In the present work the volume of the breast was determined by using a Coon's patch to construct the backplane of the image from a selection of surface points. The breast volume for all subjects except subject 5 was estimated by passing a plane through 4 corner points identified outside the boundary of the breast in the upright position and calculating the volume between the breast surface and this back plane. This calculation ignores the chest wall curvature and the thickness of the subcutaneous tissue around the breast. For subject 5 this method was not adequate so we used the software SolidWorks which made possible the generation of a curved back surface.

The overall deformation of the breast consists of two parts: first, the movement of the breast relative to the fixed points on the body, and second the changes in the skin stretch at different points on the breast surface. Efforts were made to remove the points with obvious errors. It was seen, for example, that on the areas with high curvature, when a higher number of points are necessary to capture the correct shape, the use of an inadequate number of Lagrangian marker points lead to obvious off-bound results. So these points were excluded from the final point-sets and 3D distribution maps of the obtained quantities. In the manual DIC scheme that is based on a point-cloud with a constant resolution, an increase in the number of marks may not necessarily lead to a more accurate and smooth deformation field. Since the position identification error in the manual selection procedure remains constant,

²3dMDtorso Imaging System, 3dMD, Atlanta, GA, <http://www.3dMD.com>.

³Custom system built for our research group at The University of Texas MD Anderson Cancer Center by 3dMD, Atlanta, GA

the error in manually identified length divided by a shorter gauge length scale will result in a greater overall error.

The deformation of the breast is analyzed using the standard theory of finite deformations: the deformation can be viewed as a mapping that takes any Lagrangian marker point $\mathbf{X}$ in one configuration⁴ (here we assume this to be the supine position) to the point $\mathbf{x}$ in another configuration (inclined at various angles or upright).

$$\mathbf{x} = \mathbf{X} + \mathbf{u}(\mathbf{X})$$

where the vector $\mathbf{u}(\mathbf{X})$ defines the displacement of each Lagrangian marker point. The deformation gradient tensor is then calculated as:

$$\mathbf{F} = \mathbf{I} + \frac{\partial \mathbf{u}}{\partial \mathbf{X}}$$

To reduce this three-dimensional expression to the breast skin, it is sufficient to consider the breast skin as a two-dimensional surface (either as a membrane or a shell) and examine the in-plane components of the deformation, i.e., calculation of the principal in-plane stretches (λ_1, λ_2) and the orientation of the principal deformation should be adequate. For implementation of this calculation from the point-cloud image, a three-node triangle is the simplest shape that can be used to obtain the gradient of its deformation; with this assumption, only a constant deformation gradient can be obtained at each triangular region. In other words, we are projecting the actual curved surface connecting the three nodes to the flat plane connecting the three nodes.⁵ This is illustrated in Fig. 1, where the point-cloud image of the breast (indicated by the red dots) is overlaid with the triangulation (yellow lines) of the Lagrangian marker points; both the supine and upright orientations are shown in order to visually illustrate the deformation. Two triangular elements are highlighted in green in both orientations in order to illustrate the change in position, orientation, and size. For each triangle, the constant deformation gradient tensor can be calculated from the coordinates of the three points of that triangle in the reference and deformed configurations. After obtaining $\mathbf{F}$ for each triangle, we use polar decomposition to get:

$$\mathbf{F} = \mathbf{R}\mathbf{U} = \mathbf{V}\mathbf{R} \quad \mathbf{V}\mathbf{V}^T = \mathbf{U}^T\mathbf{U} = \mathbf{F}^T\mathbf{F},$$

⁴This is the reference configuration; it is not necessarily the stress-free configuration. In fact, as we will see later in Section 3.1, the supine position is not a stress-free configuration for all points on the breast.

⁵There are two sources of error in the presented analysis. The first source of error is introduced through the measuring system: imaging hardware, 3D reconstruction algorithm, resolution, and eventually the imperfection in manual selection of marks. This error was shown to cause less than an average of 1% strain when a rigid plastic mannequin was imaged in 2 different positions (see [11]). The second source of error is due to the use of linear constant strain triangles instead of high-order elements in the calculation of deformation gradient. In simple terms, a pair of nodes on a 3D surface is connected through a curve; while in case of 3-node triangular elements, each pair is connected through a straight line. If the curvature is significant, there would be a large difference between the lengths of the actual curve and straight line. This can be interpreted as a measure of error caused by using 3-node linear triangles. We calculated this difference for all subjects in 0°, 45° and 90°. Indeed this error is minimized when the number of marks on the surface increases. In general, this error is very small: e.g., for subjects 2 and 5, with the least and most dense marking pattern, the difference between real curve length and straight line for 94% and 99% of sides is smaller than 1%, respectively. Furthermore, all elements which had a side with an error greater than 5% were eliminated from the analysis.

where $\mathbf{U}$, $\mathbf{V}$, are the right and left stretch tensors, and $\mathbf{R}$ the rotation tensor. The eigenvalues of $\mathbf{V}$ or $\mathbf{U}$ represent the principal stretch ratios ($\lambda_1 > \lambda_2$), while the eigenvectors of $\mathbf{V}$ are the corresponding orthonormal principal directions (β_1, β_2) in the current (deformed) position; for the skin, the third principal direction corresponds to the normal to the triangular element. Recall that the stretch ratio is defined as the ratio of the deformed length divided by original or undeformed length: $\lambda = l_{\text{deformed}}/l_{\text{undeformed}}$. A stretch ratio greater (or smaller) than 1.0 is associated with tension (or compression). Note that to obtain the principal directions we choose $\mathbf{V}$, since, unlike most cases in the mechanics of deformable bodies, it is more intuitive to plot the principal stretches and the corresponding direction on the current configuration corresponding to the deformed breast (upright or 45° orientation). The principal directions obtained from $\mathbf{U}$ and $\mathbf{V}$ vary by the rotation angle θ which in turn is obtained from $R = [\cos(\theta), -\sin(\theta); \sin(\theta), \cos(\theta)]$. We note that in the analysis of del Palomar et al. [8], comparison of the supine and upright shapes was performed by only comparing the displacement of pairs of points, i.e., by comparing the stretches and ignoring the rotations.

3. Results and discussion

Five female subjects volunteered to participate in this study. Informed consent was obtained and the study was approved by the Institutional Review Board. Demographic and clinical background and information are given in Table 1. The 3D images of their breasts were obtained using the custom-made 3dMD imaging system. Fig. 2 shows the frontal projection⁶ of the image with the subject in the supine, 45° inclined and upright; each row corresponds to one subject, and each column corresponds to one orientation of the image. The Lagrangian marker points can also be seen in these images. These images, the point-cloud data of the surface, the corresponding texture map, and the coordinates of the Lagrangian marker points constitute the primary data of the investigation. These images provide a wealth of quantitative and qualitative data on the definition of the breast, its volume and shape changes, its position relative to the underlying skeletal structure etc. To provide comparison to data typically reported from 2D images in the plastic surgery literature, the geometric measurements identified in Fig. 3 were performed and reported in Table 2; these include: (i) breast volume (upright), (ii) N-N, the nipple-nipple distance, (iii) ML-N, the distance from the midline to the nipple, (iv) HD-N, the height difference along the midline (ML) between horizontal lines through the left and right nipples, and (v) HD-IMF or LVP, the height difference along ML between horizontal lines through either the inframammary fold (IMF) or the lowest visible points (LVP).

3.1. Variation of the principal stretches on the breast surface

Tilting the subject from supine to upright position causes a change in the shape of the breast (see Fig. 2), the magnitude of which depends on the size of the breast, the properties of the tissue comprising the breast, and the properties of the skin. Tilting also causes large deformation in the breast skin. In order to quantify the deformation in terms of the stretch variation with position, a reference configuration must be identified. The notion of an

⁶The full set of 3D point-cloud images is provided as Supplementary Material.

unstressed reference configuration plays a major role in the formulation of a breast biomechanical model. For example, Rajagopal et al. [7] used an imaging scheme in which an MRI of the breast was obtained with the subject in the prone position with her breasts immersed in a water bath providing an unloaded buoyant condition and considered it to be the reference configuration. There are some ambiguities: first, since the volume of the breast is unchanged, the skin may not be completely unstressed but contain a prestretch resulting from the volume constraint. Second, typically, MR images do not provide Lagrangian positions that could be followed under different loading conditions. Nevertheless, Han et al. [15] discussed the possibility of using implanted fiducials to obtain such data, and Carter et al. [16] used self-adhesive MR-visible fiducial markers to the skin and obtained prone-supine MR images, with the goal of registering the prone and supine images through finite element modeling of the deformation. Their objective was to identify the location of a tumor in the interior and not shape prediction. Third, in women with large breasts, the skin is seen to be recruited from the axilla; the table cushion used in MRI technique could prevent such movement and provide a constrained view of the breast shape change. Lastly, the immersion method is not easy to use in practice. The tilt imaging procedure used in the present work provides an opportunity for identification of the reference state. While one might argue that in the supine position because the breast mass is mostly resting on the chest wall, the skin does not sustain any mechanical load and could be taken to be in the unstressed configuration, close examination of the 3D images as in Fig. 2 indicates that a portion of the breast skin is wrinkled as a result of the breast mass loading. Clearly the skin is not stress-free, and therefore not in the true unstressed configuration, at least in the neighbourhood of the wrinkled region. In fact, a unique and natural reference configuration may not exist for the entire breast and an ideal reference configuration in which the skin is unstressed everywhere may not be achievable in vivo. For convenience, we choose the supine position to be the reference configuration (with an unknown prestress and stretch distribution) and obtain the stretch distribution relative to the supine position. Fig. 4 illustrates the distribution of the major (maximum) and minor (minimum) principal stretch ratios (λ_1 , λ_2) in columns 1 and 2 corresponding to an orientation change from supine to upright, and the major principal stretch λ_1 in column 3 corresponding to an orientation change from supine to 45°; the contours of the stretches are overlaid on the textured, point-cloud image to provide a visual indication of the regions analyzed. These measurements could not be performed for subjects 3 and 5 in the region of the axilla due to occlusion of this region by the breast in the supine position. The direction of the principal stretches are shown in Fig. 4 by the vector overlays. As expected, the direction of the major stretch in all subjects is approximately along the gravity line (vertical) over much of the breast surface. Note that the stretch distribution is significantly subject-dependent while the principal direction is relatively subject-independent. Subject 1, with the least breast volume experiences very small changes in shape; the stretch remains close to unity. In contrast, subject 5, with the largest breast volume, experiences stretches as large as 1.6, particularly in the upper part of the breast, close to the axilla. However, it should be noted that the breast volume is not the sole determinant: subject 3, with a smaller volume than subject 5, also experiences large stretches, indicating that the skin thickness, skin elasticity, and substrate properties (connective tissues in the layer attaching to the underlying musculoskeletal system) must play a role in dictating breast deformation. It must be reiterated that these stretch values are

relative to the supine position and the skin in this position has an as yet undetermined stretch relative to its stress-free state. In Fig. 4 it can be seen that there is an area near the axilla which shows higher stretch ratio than other parts of the breast skin. A comprehensive FE model of the breast is currently under development in our group with the goal of using these measurements in a biomechanical finite element model in order to identify the role of the skin in supporting the breast. The rotation of the breast skin corresponding to a change from supine to upright positions is shown in the first column of Fig. 5. While these rotations appear to be negligible in most cases, in the case of subject 5, with the largest breast volume, parts of the breast may undergo considerable rotation, particularly on the upper surface of the breast.

3.2. The state of the breast skin deformation: uniaxial or biaxial?

There is extensive literature on the necessity of performing biaxial tests on skin samples in order to obtain a meaningful development and calibration of constitutive models [11]. The main argument is that since the skin is a continuous shell or membrane-like structure, testing excised and narrow samples under pure uniaxial tension will lead unrealistic effects during material characterization. On the other hand, there are relatively limited direct measurements from which to make inferences about skin response. The measurements of skin deformation presented in the previous section allow us to demonstrate the extent of uniaxiality or biaxiality of the skin stretch due to the position change, provided some assumptions are made regarding the material behavior. We pursue two approaches. First, considering the skin to be an isotropic material, measured values of the principal stretches, $(\lambda_1^{\text{measured}}, \lambda_2^{\text{measured}})$, are used to define a measure of the deviation from pure uniaxial tension. Noting that for a pure uniaxial stress state in a perfectly incompressible material, $\lambda_2^{\text{uniaxial}} = 1/\sqrt{\lambda_1^{\text{measured}}}$, the measure of uniaxiality is defined as $UM = (1 - \lambda_2^{\text{measured}}/\lambda_2^{\text{uniaxial}})$; $UM \sim 0$ implies nearly uniaxial skin deformation. Column 2 of Fig. 5 shows that this uniaxiality measure for all five subjects is in the range of 0–0.15 over most of the breast, implying predominantly uniaxial state. Next, consideration of skin as an anisotropic material requires a constitutive model for the skin; we chose the 2D fiber network model of Gasser et al. [17] which provides $\tau_1 = f(\lambda_1, \lambda_2)$, $\tau_2 = g(\lambda_1, \lambda_2)$. Detailed expressions of the functional form and calibration of this model for human skin are given by Tonge et al. [18]. We used the mean and standard deviations reported by Tonge et al. [18] to obtain a range of possible material properties, but constrained it by the Baker–Erickson inequalities to determine the admissible range for the material properties. Within this range of properties, the uniaxiality measure, UM , was recalculated: for an anisotropic material, we estimate $\lambda_2^{\text{anisotropic}}$ by setting the uniaxial stress condition: $g(\lambda_1^{\text{measured}}, \lambda_2^{\text{anisotropic}}) = 0$; we can then use the uniaxiality measure indicated above. Column 3 of Fig. 5 shows this uniaxiality measure for all five subjects with material properties derived from the average skin properties reported by Tonge et al. [18]. Comparing these with the uniaxiality measures corresponding to an isotropic material indicated in Column 2, it appears that the dominant loading and resulting stress changes could be considered as uniaxial in most parts of the breast, with the exception of the regions near the areola and axilla.

3.3. Movement of the boundaries of the breast

Identification of the boundaries of the breast is crucial in developing a biomechanical model of the breast as well as in surgical reconstructions. It is also important to know how the breast tissue moves as the subject changes from the supine position to the upright position. From an examination of the prone and supine MR images, Carter et al. [16] identified significant sliding of the breast around the torso and accounted for this in their analysis of breast deformation from prone to supine. Lee et al. [19] have used images obtained while the breast was pushed hard inward or upward, defining a fold that outlines the boundary of the breast. The 3D images obtained in this study present an opportunity to identify the breast boundaries as well as locate them with respect to the skeletal structure. In order to explore this further, we construct three representations of the supine and upright images. First, Fig. 6 shows composite images of the right breast in the supine and upright positions for subjects 1, 3 and 5. This image is constructed by juxtaposing the supine image of the right breast (left half of each image) with an upright image of the *same* breast (right half of each image); note that in order to accomplish this, the upright image has been reflected about the sagittal plane passing through the ML. The red dot in the image identifies the medial point (MP) on the right breast and the arrow points to the position of the same MP in the upright position. Second, Fig. 7 shows a sagittal section of the breast at a plane through the right nipple for subjects 1, 3 and 5; images corresponding to the supine and upright positions are superposed for comparison. A few Lagrangian marker points are also identified in these images by the yellow, red, green and blue dots. Third, a close-up view of the region near the sternal notch and clavicle is shown in Fig. 8; in these images, the red dot indicates the sternal notch which is a fixed point on the skeleton. It is identified without ambiguities associated with the movement of the skin by using the variation in the curvature in this region since this feature does not change with changes in orientation of the subject. The red dashed line in the left image indicates the distance from this fixed location to the first Lagrangian marker point on the skin in the supine position. As the subject changes to the upright position, the first Lagrangian marker moves relative to the skeleton, to the location identified by the red line with an arrow head. The displacement of the skin corresponding to this movement is 24 mm; this displacement occurs simply because the skin and the soft tissue are sliding over the skeleton in this location. Such sliding is significant in the upper part of the breast, but decreases near the IMF. Additional investigation of the anchoring of the skin to the skeleton over different parts of the body is required to gain a complete understanding of this aspect of breast movement. Finally, the distance between the sternal notch and the umbilicus was measured along the midline following the contour of the body in the supine, 45° and upright positions, and is shown in Table 3; for subject 1, there is almost no change in this length, while for the other subjects, there is somewhere between 10 mm and 20 mm change in the length indicating a significant decrease in the length of the skin as the subject changes position from upright to supine. Together, these images and measurements point to a substantial movement of the breast skin and tissue relative to the underlying musculoskeletal structures, and to the importance of incorporating such mobility in the development of biomechanical models.

4. Conclusion

Three-dimensional imaging and image correlation have been used to determine the variation of breast skin deformation as the subject orientation is altered from the supine to the upright position. It is demonstrated that a reliable estimate for the full field distribution of the breast skin deformation can be obtained through proper marking on the breast, quantitative 3D imaging and 3D-DIC. A change in subject's position from supine to upright can result in significant stretches in some parts of the breast skin, especially above the nipple. The maximum of the major principal stretch ratio of the skin is different in different subjects and varies in the range of 1.25–1.60. It is also found that the boundaries of the breast move significantly relative to the underlying musculoskeletal structures and other fixed points such as the sternal notch; complete characterization of the underlying reasons for such movement and quantitative measurements of the range of such movements is crucial for the development and validation of biomechanical breast models based on finite element formulations. The present study also indicates the necessity of performing similar studies on other subjects with a range of breast sizes and body habitus in order to facilitate building patient-specific models for breast reconstruction surgery.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.medengphy.2014.09.016>

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Fig. 1.

Point-cloud image of the breast of subject 5 in the supine (left image) and upright (right image) positions with a false color map. The triangulated wire-mesh overlay connects the Lagrangian marker points that were identified in the two orientations and provides an illustration of the deformation of the breast skin; two such triangles are highlighted in green to provide visual cue of the change in size and orientation. The perspective of the left image is rotated by 15° with respect to the cranial-caudal axis in order to increase the visibility of the breasts. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2.

Frontal projection of the 3D-point cloud images with the subject tilted in the supine, inclined 45° and upright positions. Each row corresponds to one subject, and each column corresponds to one orientation of the image. The line and dot patterns drawn with surgical marker pens are used to identify the Lagrangian marker points. Note that the left breast of subject 4 was not marked and therefore deformation measurements could not be made on this breast.

Fig. 3.

Definition of fiducial points and distances. The blue dots indicate the nipple (N), the green dots indicate either the inframammary fold (IMF) or the lowest visible point (LVP), and the red dots indicate the anterior axillary point. The left-right asymmetry is indicated by the height difference along the midline (ML, white dashed line) between the horizontal lines (dashed yellow lines) passing through the left and right nipples (HD-N) and the horizontal lines (yellow solid lines) passing through the IMF or LVP of the left and right breasts, and denoted as HD-IMF or LVP. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4.

The first and second columns show the maximum and minimum principal stretch ratios when the subject is tilted from 0 to 90°. The third column shows the maximum principal stretch ratio when the subject is tilted from 0 to 45°. The corresponding principal directions are shown by black vectors. The supine position is used as the reference configuration. Note that the color bar for each column is found in the images corresponding to subject 4; as noted earlier, deformation measurements could not be made on the left breast of this subject.

Fig. 5.

The rotation angle (left column in degrees) and the uniaxiality measure (isotropic model – middle column and anisotropic model – right column) on the breast skin when the subject is tilted from supine to upright with the former as the reference configuration. Note that the color bar for each column is found in the images corresponding to subject 4; also as noted earlier, measurements could not be made on the left breast of this subject.

Fig. 6.

A graphical comparison of the shape change of the right breast for subjects 1, 3 and 5 is shown. The left half of each image shows the right breast in the supine position; the right half of the image shows the same right breast in the upright position, but the image has been reflected about the sagittal plane passing through the ML in order to facilitate direct visual comparison. Note that as a result of the inversion, the numbers are seen as mirror images. The red dot in the image identifies the medial point on the right breast and the arrow points to the position of the same point as the subject moves from the supine to the upright position. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 7.

A plane was passed through the chest wall and breast at the nipple to depict the sagittal profiles of the breast with the subject tilted in the 0° (black outline) and 90° (blue outline) positions for subjects 1, 3 and 5. Note that these planes for 0° and 90° profiles have different angles relative to the chest wall due to the severe rotation of the breast mass particularly in models 3 and 5. The yellow, red, green and blue dots correspond to fiducial marks that were identified in both orientations and provide an indication of the deformation of the breast skin. Since the rotation of this plane cannot be taken into account in a 2D analysis, these profiles are not ultimately sufficient for realistic prediction of the whole breast shape. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8.

Close-up views of the supine (left) and upright (right) images of subject 3 are shown to illustrate the significant movement of the skin surface relative to the skeletal structure. The red dot in both images indicates the sternal notch identified as a fixed point in the skeleton by the curvature of this region. The red dashed line in the left image indicates the distance from the sternal notch to the first Lagrangian marker point on the skin with the subject tilted in the supine position. As the subject changes to the upright position, the first Lagrangian marker point moves relative to the sternal notch, to the location identified by the tip of the red arrow head in the right image. The displacement of the skin corresponding to this change in position is ~24 mm and is indicated by the black arrow; this displacement occurs simply because the skin is sliding over the skeleton in this location. The white line is a reference scale mark that is 32 mm long. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Demographic and physical data on the 5 subjects used in this study. Body fat percentage was measured with an OMRON HBF-306C device.

Table 1

	1	2	3	4	5
Age (years)	21	53	45	44	21
Weight (kg)	54.5	53.6	65.9	66.4	86.8
Height (cm)	164.5	164.5	158.5	158.5	155.4
Body mass index	19	20	27	27	36
Body fat (%)	21	na	33	34	39
Bra size	32	36	34	36	38
Cup size (A, B, C, D)	B	B	D	C	DD
Race and ethnicity	W-NH	W-NH	W-NH	W-NH	W-H
Previous breast surgery	None	TRAM flap – left breast	None	None	None

W: White, H: Hispanic, NH: non-Hispanic.

Table 2

The fiducial measurements of a subject's breasts with the subject tilted to supine and upright positions.

	Subject 1			Subject 2			Subject 3			Subject 4			Subject 5							
	Supine		Upright	Supine		Upright	Supine		Upright	Supine		Upright	Supine		Upright					
	R	L		R	L		R	L		R	L		R	L						
Volume	320	300		340	420		680	n/m		840	850		1330	n/m						
ML-N	119	118	121	112	98	111	89	108	134	139	141	146	145	143	154	156	198	205	195	197
N-N	232		224		204		191		272		199		274		229		388		270	
HD Ns	-10		-6		-8		2		24		13		-19		-15		8		4	
HD IMFs or LVPs	-7		-4		-6		1		11		7		-10		-4		n/m		3	

N: nipple; ML: midline; IMF: inframammary fold; LVP: lowest visible point. The identification of these fiducial points and the definitions of distances HD-N and HD-IMF or LVP are given in Fig. 3. All length measurements are in mm and volume measurements are in mL. In the supine position, the breast volume was not calculated due to the lack of a widely accepted methodology. n/m: not measurable primarily due to holes in the images.

Table 3

Distance (mm) between the Lagrangian marker point near the sternal notch and the umbilicus with the subject tilted at 3 different orientations: 0°, 45° and 90°.

Subject	0°	45°	90°
1	344	342	344
2	345	361	364
3	382	399	397
4	n/m	n/m	n/m
5	393	410	404

n/m: not measurable.