

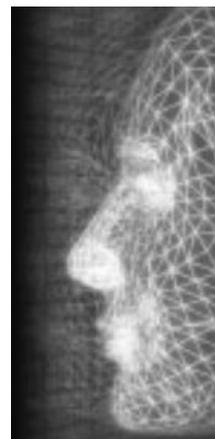
A breast modeler based on analysis of breast scans

By Hyewon Seo*, Frederic Cordier and Kyunghi Hong

The advent of 3D scanning technology has allowed effective measurement and analysis of breast size and shape, attracting interests by plastic surgeons, brassier designers, etc. Much work remains, however, before 3D scanning systems can be successfully used in automated analysis and synthesis of the breast—filtering noise, filling holes, and, in case a statistical analysis is desired, finding correspondence among each scan data. Moreover, analysis of a sagged breast is difficult to obtain, due to occlusions. In this paper, we address the problems and specific issues of using 3D scan data for the analysis and synthesis of breast models. The goal of our work is to build a breast modeler which can help both surgeons and garment designers in analyzing breast volume and surface measurements. Given enough samples of scanned breasts, our modeler can generate highly realistic breast shape, with some expected and consistent variability. Copyright © 2007 John Wiley & Sons, Ltd.

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Introduction

3D digital imaging of the breast can be an invaluable tool for plastic surgery, underwear manufacturing, and a variety of other applications, given its unique ability to acquire 3D coordinates of key points with high resolution. With its potential to critically analyze differences and commonalities in size and shape, 3D scanners have started to gain popularity both in academia and in commercial applications [14]. Unfortunately, there remain several problems to be addressed before this technology can be effectively harnessed: (i) Obtaining a complete model of a particular person is often difficult or impossible.¹ Incomplete surface data is often obtained, even with a carefully set scanning environment. Scanning sagged breasts present a tougher challenge, as part of the base breast cannot be observed due to the occlusion. (ii) From the surface measurement we need to determine valid and reliable breast volume, one of the crucial measurements on breasts.² (iii) 3D imaging technique is restricted to recording shapes that can be observed. In our work, we focus on solving the

first two problems, which, to the best of our knowledge, have not been discussed in sufficient detail previously. Previously captured shapes of nude breast³ have been used, some of which are sagged ones. On the whole, we have developed a framework for the post-processing and statistical analysis of multiple scans of nude breasts, and for the synthesis of new breast models meeting a variety of user-supplied constraints. Unlike existing modelers which usually provide only sparse measurements around the breast, such as breast girth and cup size, our breast modeler allows a more complete set of parameters, including breast volume and surface distance between major landmark points. This paper contains three main steps:

- We have developed a set of tools that is needed for post-processing breast scans. These tools are used to deform a template mesh onto each of the scans, and to measure the volume. In the process, we address details that are important for processing sagged breast, a considerably difficult task due to its self-occluding nature. Based on the observation data acquired from the previous work,³ we handle sagged breasts by merging a pair of measurements—the original sagged breast and a lifted breast using tape, which have been acquired in accordance to the procedure described in Reference 3.

*Correspondence to: H. Seo, Department of Computer Science and Engineering, Chungnam National University, 220 Kung-dong, Yuseoung-gu, Daejeon, Korea. E-mail: hseo@cnu.ac.kr

- We then carry out statistical analysis and model shape variation that occurs across different individual breasts. The shape variation is represented by using principal component analysis (PCA), which induces a low-dimensional subspace of breast shape deformations. This result, combined with an appropriate approximating model, is used for generating a complete surface mesh given only a partial specification of the desired shape—the location of landmark points, for instance.
- We construct a modeler based on the statistical model of breast shape. Starting from the dataset, a continuous range of shape is obtained through approximating linear combination of weighted Gaussian functions. Upon the user-supplied constraints, these functions supply the template mesh an appropriate deformation, so that the requirements are met. This allows for the synthesis of realistic breast shape, whose exact shape is not present in the original set of scans. While the idea of modeling continuous range of shapes from a set of sparse set of high quality samples have been previously explored, we believe that our modeler offers a sophisticated and more complete control over the breast shape.

Related Work

There have been several works on breast modeling that make use of scan data. Some of them try to solve general problems of surface scanning, such as post-processing and building mathematical representation of the surface data. Others focus on problems that are specific to the breast. Lee *et al.*³ have proposed a measurement protocol to facilitate the feature analysis on the surface data after the scan. Landmarks have been placed on the 3D image to indicate the breast border, so that breast volumes could easily be calculated on the scans. They have compared the intra-operatively measured breast volumes and the calculated ones on 3D images. Losken *et al.*⁴ have carried out similar comparative study, where the volume measurements on the breast scans are compared to those that are measured by water displacement method. Their specific focus has been on validating 3D imaging technology for breast volume and surface measurements as used in plastic surgery.

Recent studies report more mature works on processing scanned images, such as automating the post-processing and correspondence finding, and parameterized control over morphable models.⁵⁻⁷ However, the

scan images they use have been acquired for general anthropometric studies, thus scans exhibiting nude breasts are extremely rare. In this work, we solve specific problems of, and address issues of surface methods to a breast modeling based on analysis of 3D scans.

Data Acquisition and Processing Data Meshes

Scanning and Landmarking

We have used 3D images of 28 nude breasts (28 subjects of age between 40 and 60, one breast from each) that have been acquired using a phase-shifting-moiré topography (Intek Plus Co, Ltd.) scanner. The scanner uses a 640 × 480 CCD camera and has approximately 90-degree surface coverage. We have obtained images of the right side of the upper body, with the focus of the camera fixed on the right breast of the subject. A set of markers have been attached along the borderline of the breast, using the measurement protocol as described in Reference 3. Required landmarks include center of thorax (CoT) and other points (BBP, OBP, UBP, IBP) that are used to define breast boundaries. The description on the major landmarks is summarized in Table 1. For the extremely sagged breast, two datasets have been obtained: The first surface data has been captured normally, and, for the second data, breasts have been lifted using semi-transparent tapes so that the lower breast line could be scanned. As to one-dimensional

Land-marks	Definition
BP	Bust point
IBP	Inner breast point
OBP	Outer breast point. The midpoint between the front armpit point (FAP) and the intersection point of FAP-SWP, and the horizontal line passing through the BBP
UBP	Upper breast point. The highest point along the breast line
BBP	Bottom breast point. Minimum point in the x profile
SWP	Side waist point
CoT	Center of thorax
FNP	Front neck point

Table 1. Landmark symbols and definitions

measures around the full torso, the underbust girth and the breast girth have been measured manually on the subjects with traditional tape measuring method, at the time of the scanning.

The result of each of the scanning is a texture-mapped 3D mesh. Upon loading the mesh, the user is asked to identify each of the landmark points on the mesh. These landmark or feature points are clearly visible from the mesh and its texture (see Figure 1(b)).

Correspondence

Meshes acquired from 3D scanner are of different topologies, depending on the environment and the subject at the time of scanning. In order to analyze the variation in breast shape, corresponding points on each surface must be compared. We can use the landmark positions (see Figure 1(b)) to find major correspondence, that is, the corresponding locations of each landmark point on the surface. However, these points represent only sparse set of (less than 1%, dozens out of several thousand, in number of vertices) the original surface data. To analyze the full shape of an individual scan, we need to establish correspondence between many more points densely located over the surface. This means correspondence among the scanned breast must be found.

Similarly to the previous work by Seo and Magnat-Thalman⁷, we assume that the topology of the surface is known in *a priori*, which constitutes our template mesh (see Figure 1(a)). For each scanned data, we will deform this template mesh so that its shape is as close as possible to the individual surface. During the deformation process, we match the corresponding landmarks, that is, the BP of the template mesh will map to the BP of the scan data, BBP to the BBP, IBP to the

IBP, and so on. In addition, we minimize the overall distortion of the template mesh, as described later in this paper. The result is a deformed template mesh that is brought into the shape of, and lies in correspondence with, each of the data meshes.

The deformation process operates in a coarse-to-fine manner, and is composed of two steps. We start by using the location of landmark points on the data mesh to find rough mapping of the template mesh in the coarse level (see Figure 1(a)–(c)). After the rough matching, we obtain a finer level of the template mesh by subdividing each of its triangle patches into more than hundred smaller triangles (see Figure 1(d)). The next step of the deformation process iteratively improves the matching quality by repeatedly projecting template vertices to the nearest point on the scanned surface, followed by mesh relaxation. A more detail description on each step is provided in what follows.

Rough Mapping of the Template Mesh. Our template model is essentially a triangle surface of a breast that contains all the points we would like to match. In order to accomplish the matching process in a coarse-to-fine manner, we have defined two levels of detail on the template mesh, a rough mesh with a very small number of triangles and a fine mesh with a thousand vertices. As mentioned earlier in this section, the lower level mesh is a triangle patch connecting the landmark points on the template. We have also defined surface measure lines on it, which are used to obtain 1D measurements on the surface at any time during the analysis and synthesis. What constitutes our template model is listed below:

Landmarks: For the matching we adopt a feature-based method, which require a set of corresponding markers between each data mesh and the template. Sub-

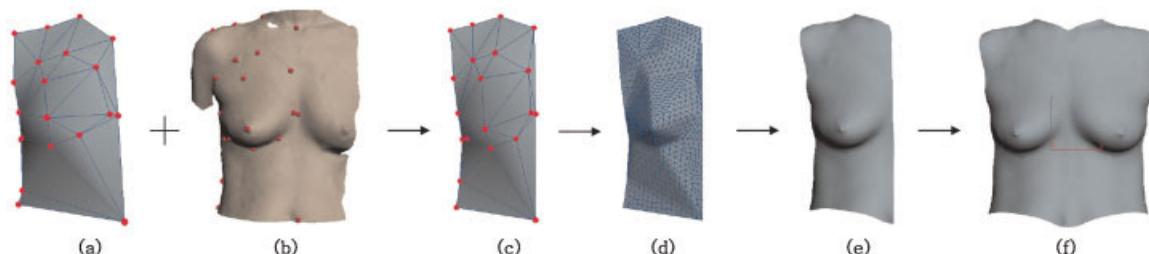


Figure 1. Deforming a template mesh. (a) Template mesh prior to the pre-processing, (b) target scanned mesh, (c) deformation of the lower level template mesh by relocating feature points, (d) higher level mesh is obtained by subdividing each patch in the mesh, (e) deformation of the higher level mesh and (f) mirroring to acquire a symmetric mesh.

sequently, the same set of landmark points as on the scanned meshes is also used for the template model. Most of these points are a subset of the landmarks as defined by Lee *et al.*³ A number of additional landmark points are defined around the boundary of the patch. These landmarks are manually placed on the template surface once, and the indices of the labeled vertices are stored in the system throughout the process.

Lower level mesh: We construct the lower level of our template mesh by connecting as a triangle patch the landmarks that have been located on a scan data (see Figure 1(a)). The vertices to be connected are chosen such that the number of narrow triangles (or slivers) is minimized in the patch.

Higher level mesh: The higher level mesh is obtained by subdividing each triangle of the lower level template mesh into dozens of finer triangles, as shown in Figure 1(c) and (d). The subdivision level is set to 8 in our paper, which means each edge of a triangle is subdivided into 8 smaller edges, resulting in 4 by 4 (=64) smaller triangles. The subdivision level can be adjusted by the user depending on the desired level of detail of the shape to be analyzed and synthesized.

Surface measure line: Location of landmarks enables us to take all important measurements about the breast size and shape—BP<—>OBP, BP<—>IBP, BP<—>UBP, BP<—>BBP, and so on. In order to take these measurements on our scan data as well as on synthesized models, we create these measure line segments on the initial template mesh. We then ‘glue’ or attach each line segment on the template mesh. The attachment is accomplished by first computing for each point on the line segment the closest triangle on the template mesh and its barycentric coordinate in that triangle. Each time the template undergoes deformation, the barycentric coordinates are used to update the location of every vertex on the line segments. As a result, the measure line maintains consistent location relative to the connecting landmarks, enabling us to measure the template mesh at any time.

Non-Rigid Registration. The next step in the data preparation pipeline is to register the template mesh with each of the scanned meshes in our dataset, so that every scan data lies in correspondence with each other. The overall process is illustrated in Figure 1. We proceed with the coarse level of the template mesh and relocate each vertex on the template mesh onto the corresponding landmark position on the target scan mesh (Figure 1 (c)). Next, we subdivide each patch comprising the

template mesh to obtain a higher level of mesh. We then apply the method of Seo and Magnenat-Thalmann⁷ to accomplish the registration of the template mesh with the scan data at the higher level. The basic idea is to repeatedly alternate projection of the vertices on the template mesh to the nearest point on the scanned surface and mesh relaxation to lower the distortion of the template mesh. For each vertex on the template mesh, the closest entity of the scan mesh is computed using V-Collide, a collision detection library;⁸ we then move the vertex to its closest point on the target scan. The mesh after such vertex displacement may have a high degree of distortion, since the destination of each vertex is computed independently. The relaxation process considers each edge of the template mesh as a spring—restoring forces are applied to each edge so that the vertices are moved in a way to minimize the edge-length difference between the original template mesh and the fitted one. While the pre-determined landmark points are fixed, the vertex distribution of the template mesh will become more regular, but with a loss of fitting accuracy. By repeating the above procedure, the fitting accuracy of the template mesh is improved iteratively, which means the shape difference between the template and the scan model is minimized. Some example scans from our dataset after the fitting are shown in Figure 2.

Attribute Parameters. At the time of completing the registration, a measurement process is carried out to extract attribute parameters that describe the shape and the size of the breast. As listed in Table 2, these parameters include surface distances between the BP and other major landmarks around the borderline of breast. Once the registration is completed, simply measuring the length of the surface measure line is sufficient, since the surface measure lines stay at the same location relatively to the template mesh through the matching deformation. We also measure the volume of the breast, as measured by the method described in the next section.

Assumptions and Representations

As a result of our pre-processing, we can assume that each data mesh has the same set of points and triangles, albeit in different forms (whose shape approximates well the surface in the original scan). Several of the resulting meshes are displayed in Figure 2. Since we have used two-layer model in the pre-processing phase,

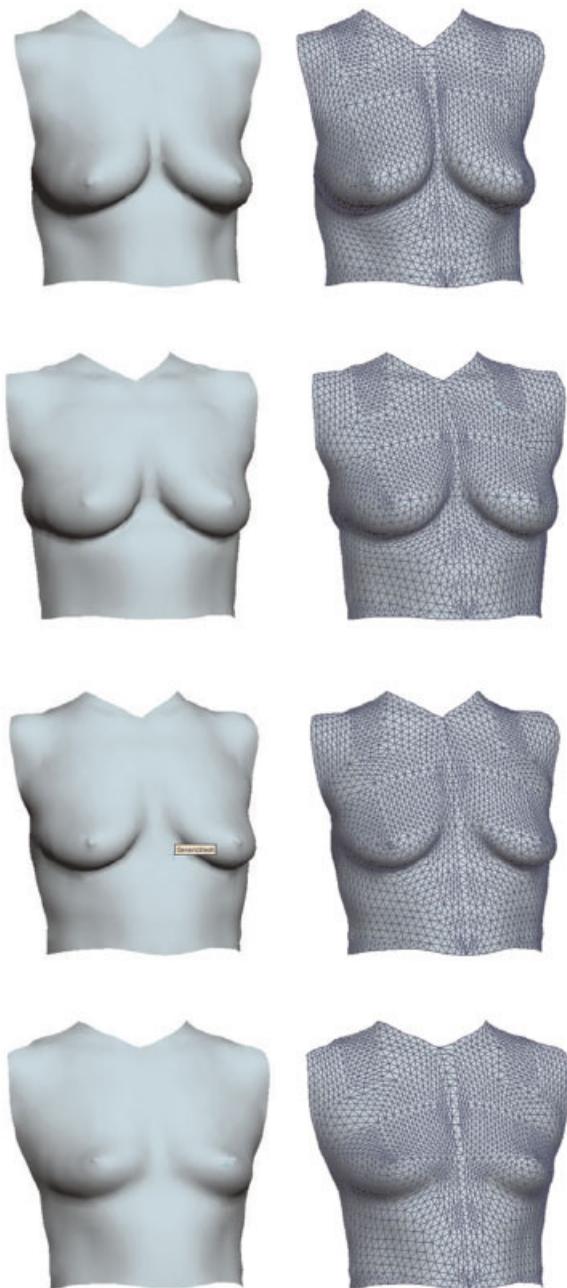


Figure 2. Template mesh registered with several example scans in our dataset. The template mesh after the deformation has been ‘mirrored’ in order to obtain the full coverage of the frontal torso.

we have, for each data mesh, a pair of vectors representing the vertex locations as denoted by

$$v_j = (d_x^1, d_y^1, d_z^1, \dots, d_y^m, d_z^m)^T \in R^{3m}$$

Parameters	Description
BP↔BBP	Surface distance between BP and BBP
BP↔IBP	Surface distance between BP and IBP
BP↔OBP	Surface distance between BP and OBP
BP↔UBP	Surface distance between BP and UBP
Underbust girth	Horizontal girth of the body immediately below the breasts
Breast girth	Maximum circumference of the trunk measured at bust height
Breast volume	Volume of the closed surface virtually detached along the borderline of breast

Table 2. Attribute parameters

where d_x^1, d_y^1 , and d_z^1 are respectively the coordinate of vertex i along the x, y , and z axis, m the number of vertices of the template mesh at the higher level, and j the index of the scan data. In our case each shape vector contains 5871 elements ($m=1957$) and there are 28 number of vectors. The origin of the coordinate system is the CoT, the orientation aligned with the global axis. We therefore represent the geometry by a breast vector D , representing non-rigid vertex displacements of the template mesh to describe the detail shape.

While it is not always the case in reality, we assume symmetric breasts: observations are made only on the right, and our modeler generates the other side to complete the anterior part of the torso by ‘mirroring’, as illustrated in Figure 1(f).

Sagged Breast

Sagged breasts are difficult to be scanned and modeled, due to occlusions. The immediate problem with a sagged breast is the impossibility of its complete observation by a surface measurement—neither the bottom line of the base breast nor the lower bust can be fully observed using a 3D scanner. Eight out of twenty-eight breasts were sagged ones in our dataset. Another problem with sagged breasts is the difficulty in finding correspondence, which is also related to the first one. If we simply use a usual correspondence finding algorithm, the bottom of the breast base of non-sagged breasts will erroneously be matched to the intersection point between the sagged breast and the chest wall, due to the non-detected part of the sagged breasts.

Fortunately, a pair of scans has been available in our dataset, in case the breasts are sagged. Apart from a normally taken breast scan, a second scan has been acquired for the same breast but lifted using a tape. Once the two scanned meshes are merged and overlapped properly, we next perform the registration of the template onto the original sagged breast and the taped breast separately, using the method as described in ‘Correspondence’ section. We then compute the vertex position of the final template by a weighted combination of the vertex positions of the two template models. As shown in Figure 3(c), the two template meshes after the fitting are aligned together by adjusting their positions and orientations, so that they are well-aligned to each other. Ideally, the difference between the two meshes should appear only around the breast bulk, but in reality, the differences can be observed all over the surfaces, albeit relatively small. This is contributable to changes in breathing status and pose of the subject at times of different scans. We use Direct Set Method⁹ to find the position and orientation of a template mesh onto the other one, in a best matching way. The error of the matching is measured by the sum of distances of corresponding vertices. In order to prohibit vertices around the breast region from influencing the matching result, we exclude from the distance sum vertices that constitute the breast bulk and underbreast, which have been pre-selected through a user interface.

Once the alignment has been made, we take the first template (matching with the normally taken breast scan) and adjust locations of its vertices near the bottom of the breast, by taking the location values of their correspond-

ing vertices from the second template (matching with the taped scan). The result is largely identical to the normally taken breast scan, but with complete geometry of the breast bottom.

Breast Volume Measurement

Breast volume is one of the crucial measurements not only in the design of brassiere and form-fitting garments, but also in pre-operative planning and post-operative evaluation of the results in mammoplasty. There are several methods suggested by different authors^{4,10} but there is still no commonly accepted standard method for measuring breast volume. In surgery, for instance, many surgeons still rely on visual estimations or intra-operative inspection to measure differences in volume between breasts and differences in volume between the mammary prosthesis to be used and the existing breast.²

Loughry *et al.*¹⁰ have adopted a molding-based measurement method that is analogous to using gypsum casts of nude breasts. Base measurement planes were used to close the surface defined by breast boundary, and, to measure the volume inside. The volume measured in this method did not reflect well the curvy nature of the breast boundary, since the base plane for the measurement was planar. Lee *et al.*³ have used curved bottom line and instead, which is arguably more natural definition of breast boundary. However, no description was provided about volume measure.

The volume of the closed surface of the breast region could be measured simply by measuring the volume of

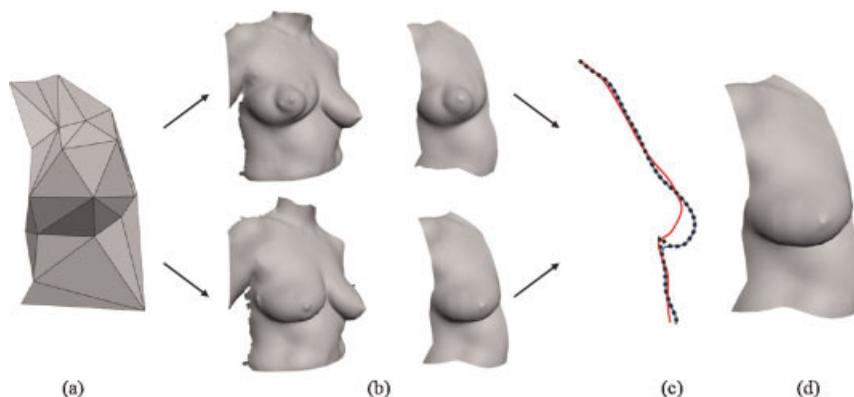


Figure 3. Reconstruction of a sagged breast: (a) The template model, (b) fitting of the template model on the mesh of the taped and non-taped breast, (c) the profile view of the taped (red), non-taped (blue), and final model (dotted) and (d) the final model computed with a weighted combination of the two models.

all tetrahedrons defined by the mesh triangles and a common arbitrary origin point. This will work well in practice, even for sagged breasts. Slicing the closed surface by a plane into many numbers of slices and measuring the surface area of each slice could be adopted here, but then we need to approximate the surface area. Moreover, it would be highly costly.

In this study we adopt Gauss' theorem for calculating the volume of a closed surface. When combined with some sensible simplification, this method can be beneficial in terms of computational cost. To our knowledge, the first paper to report successful calculation of volume using Gauss' theorem is by Matyka¹¹. In his pressure-volume model, he has shown a two-dimensional implementation that employed Gauss' theorem to calculate exact area of a simulated soft body. 2D volume (i.e., surface area) of a closed surface could be computed easily and efficiently. We can extend this idea to 3D volume calculation to deal with breast bulk that is separated from its chest wall, and closed by base surface that shares its boundary curve.

We first show how to generate a closed surface representing the breast bulk. The overall process is illustrated in Figure 4. We first separate the breast bulk from the initial (fitted template) mesh, by separating the breast region along the breast boundary curve that smoothly interpolates landmarks around the breast region (BBP, IBP, UBP, OBP) (see Figure 4(c)). We then fill the hole in the remaining mesh by adopting the radial basis function (RBF) representation of the surface.¹² As a result, a hole-free surface representing the chest-wall base is generated, as shown in Figure 4(d). The next step is to close each of the two surfaces (shown in Figure 4(a) and (d)) using a same base plane. We generate the base plane using boundary points of the initial surface (Figure 4(a)), and use the same plane for the other surface (Figure 4(d)). Once the surfaces are closed, it is possible to compute their volumes using Gauss' theorem. We take the difference between the two volume measures as the volume of the breast bulk.

Gauss's Theorem relates the divergence of a vector field within a volume to the flux of a vector field through a closed surface by the following:

$$\iiint_V \nabla \cdot F dv = \iint_s F \cdot da \quad (1)$$

where the surface s encloses the volume V , and ∇ is defined by

$$\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right).$$

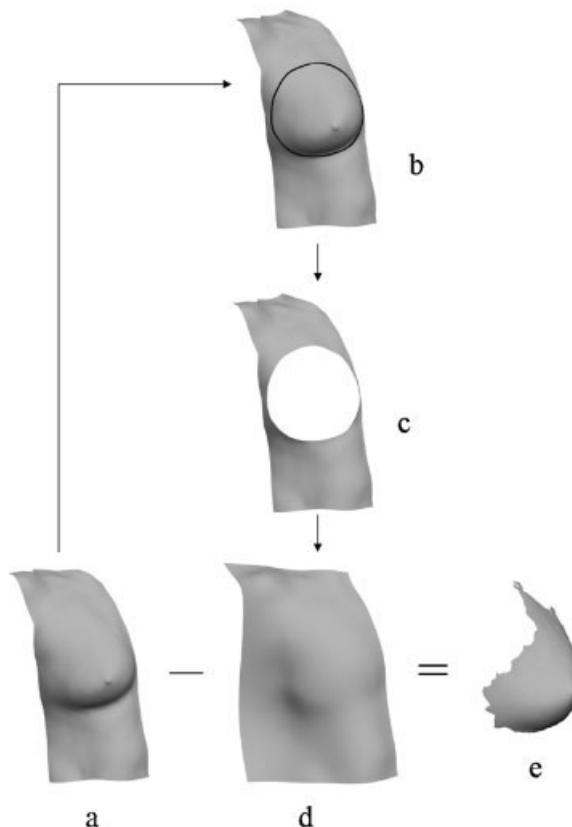


Figure 4. Computation of the breast volume; (a) the fitted template model, (b,c) cutting of the breast along the breast boundary, (d) filling of the hole using RBF, and (e) computation of the volume difference.

Suppose F is set to $F(x,y,z)=(x,0,0)$, then the innards of the triple integral in Equation (1) can be reduced to one:

$$\nabla \cdot F = x \cdot \frac{\partial}{\partial x} + 0 \cdot \frac{\partial}{\partial y} + 0 \cdot \frac{\partial}{\partial z} = \frac{\partial x}{\partial x} = 1$$

This reduction lets us write:

$$\iiint_V dv = \iint_s F \cdot da \quad (2)$$

Equation (2) tells us that the flux of the vector field F through the closed surface s is equal to the volume enclosed by s . When s is defined by a set of triangles, the enclosed volume is equal to the sum of the flux of F through every triangle. If we parameterize the triangle $\{v_1, v_2, v_3\}$ by $s(u,v) = v_1 + u e_1 + v e_2$, where $e_1 = v_2 - v_1$, $e_2 = v_3 - v_1$, the evaluation of $s(u,v)$ yields any point on the triangle for u on $[0,1]$ and v on $[0,1-u]$. Under this parameterization da from Equation (2) can be rewritten

as $dn = (e_1 \times e_2) dvdu$. The flux of F through the triangle $\{v_1, v_2, v_3\}$ now becomes:

$$\begin{aligned} \Phi &= \iint F(s(u, v)) \cdot (e_1 \times e_2) dvdu \\ &= \iint (v_{1x} + ue_{1x} + ve_{2x})(e_{1y}e_{2z} - e_{1z}e_{2y}) dvdu \end{aligned} \quad (3)$$

where the integral is evaluated through u on $[0,1]$ and v on $[0,1-u]$. The analytical solution to Equation (3) can be written as:

$$\begin{aligned} \Phi &= \frac{1}{6}((v_{2y} - v_{1y})(v_{3z} - v_{1z}) - (v_{2z} - v_{1z}) \\ &\quad \times (v_{3y} - v_{1y}))(v_{1x} + v_{2x} + v_{3x}) \end{aligned} \quad (4)$$

The right hand side of Equation (4) yields the flux of F through the triangle $\{v_1, v_2, v_3\}$. Given a closed and clockwise wound triangle set $\{v_{i1}, v_{i2}, v_{i3}\}$ for $i=0,1, \dots, n$, the enclosed volume is computed by evaluating the following sum:

$$\begin{aligned} V &= \frac{1}{6} \sum_{i=1}^n ((v_{i2y} - v_{i1y})(v_{i3z} - v_{i1z}) \\ &\quad - (v_{i2z} - v_{i1z})(v_{i3y} - v_{i1y}))(v_{i1x} + v_{i2x} + v_{i3x}) \end{aligned}$$

Modeler

Principal Component Analysis (PCA)

Once the deformation of the template mesh is complete as described previously, we are given with a set of shape vectors $v_j, j=1, \dots, 28$. We are now ready to apply statistical methods, such as mean or multivariate analysis. In this work, we have applied the PCA on v_j 's. A standard PCA decomposition as described by Press *et al.*⁹ allows us to find the directions of the largest variation among multiple shapes, which have been successfully adopted in analyzing and modeling human faces⁵ and bodies.^{6,7} For example, the models shown in Figure 5 are constructed by setting weights of a specific principle component (PC) vary within a range of values, while all the other weights to other PCs were set to 0. They indicate that the direction of greatest variation in our breast shapes is the underbust girth, combined with the sagginess of the breast. Similarly, the second most significant direction of variation is the inward/outward direction of the breast, also combined with the sagginess of the breast and the underbust girth. The third and fourth direction explains the variation in the age of the breast and upward/downward (sagged) direction of the breast, respectively.

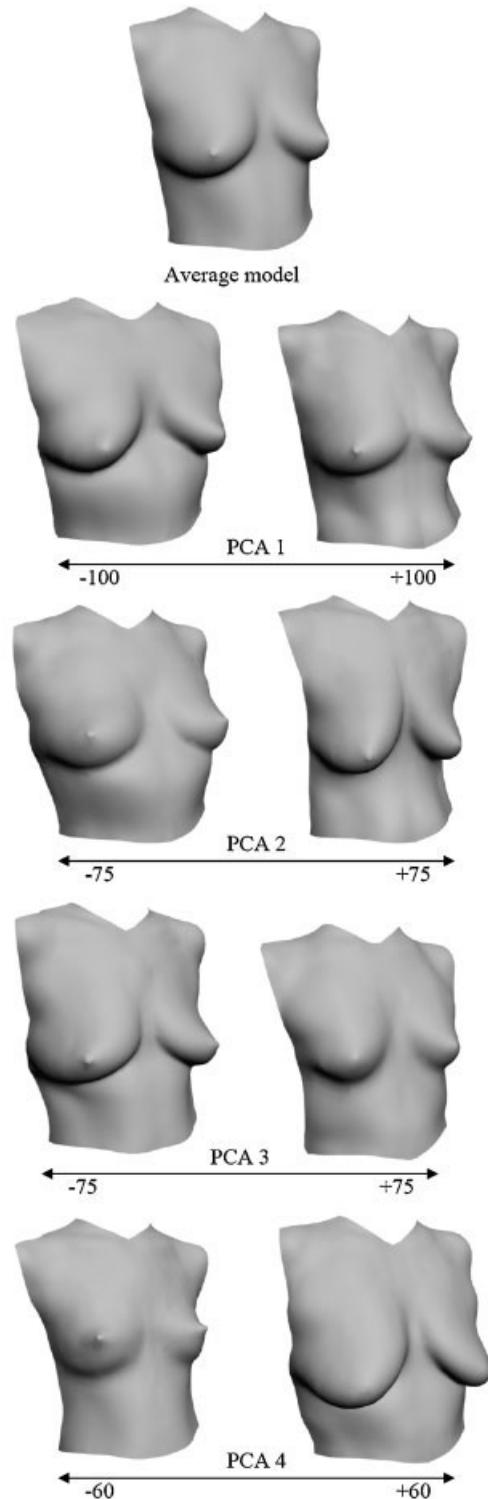


Figure 5. The first four principle components (PCs) in the breast shape space encode the variability due to different shape across different individuals.

A useful by-product of PCA is the ability to reduce the dimension of the vector used to represent individual data. After computing the component vectors (eigenvectors) \mathbf{e}_k of the covariance matrix of the shape vector set, we have a new representation of the shape vector:

$$s_j = m_v + \sum_{k=1}^{3m-1} (w_j)_k e_k$$

The component vectors are arranged in an order so that their corresponding eigenvalues descend. The key feature of PCA is that, we can reduce the number of components to, say, 30 or fewer and still reconstruct shapes that are close to the original ones. Thus, instead of keeping all $3n-1$ elements, we use \mathbf{w}_j containing only 30 elements to represent each shape in the dataset:

$$\hat{s}_j = m_v + \sum_{k=1}^{30} (w_j)_k e_k$$

Model Generation

As mentioned earlier, our goal is to synthesize new breast shapes in a controllable way, and not just reconstruct the shapes that have been measured. To accomplish this task, we built a linear model that relates the user-supplied parameters to the shape of the breast. The user-supplied parameters must be intuitive, and, although it is not obligatory, it is desirable that the parameters are uncorrelated. In our study, the user can control the breast attributes as listed in Table 2.

We first build an orthonormal parameter space by applying PCA on the set of attribute parameters collected from the scan data. We denote the normalized attribute parameter set as \mathbf{x}_j that characterizes the breast shape as denoted by the eigen weights \mathbf{w}_j of j th scan data. Based on the set of \mathbf{x}_j and \mathbf{w}_j , $j = 1, 2, \dots, 28$, $\mathbf{w}_j \in \mathbb{R}^{30}$, we build a set of interpolation functions that connects the attribute vector space to the breast shape space. We first tried to build a linear model, but the number of samples was rather small, and the mapping could not be well described by a linear model. To account for the relatively large residuals, we use RBF to build the interpolation functions, as denoted by:

$$p_k(x) = \sum_{j=1}^{28} (R_k)_j (d_j(x))$$

Note that the above formulation has a set of radial basis for each PC k ($k = 1, \dots, 30$). R_k 's are the radial basis function associated with \mathbf{w}_k and $d_j(x)$ is a measure of the

distance between x and \mathbf{x}_j , $j = 1, \dots, 28$. Given a set of pairs $(\mathbf{x}_j, \mathbf{w}_j)$, we solve for the weights of each radial basis $(R_k)_j$.

Implementation and Results

Both the modeler and the pre-processing software currently perform on a PC with Windows NT environment as a 3ds max [13] plug-in. The interactive specification of the target feature points on the scan mesh takes about a minute. The matching process works with user guidance, although it could be implemented as a fully automatic process simply by continuing the iterative fitting process until an error threshold is met. Upon receiving the desired attribute parameters from the user, the computation of a new breast shape works at an interactive rate, bringing a new corresponding model almost instantly.

Conclusion and Future Work

This paper has presented a complete workflow for measuring, analyzing, and synthesizing women's nude breast. Accounting for the sagged breast is a specificity of our model. Overall we explored a problem of breast, not comprehensively addressed previously in the literature.

The efficiency is gained due to the fact that a model is generated by interpolating example shapes in the scan dataset. The user-supplied parameters are used to determine the weight of the shape interpolation. As a result, a user simply has to supply the modeler with a set of attributes to obtain a model that best reflects the given attributes.

Whenever there is a new scan data one needs to study, which preferably has been scanned with landmarks attached at the time of scanning, he or she loads the mesh (or two meshes in case the breast is sagged, one that has been scanned normally and the second one with tape) inside the modeler and identifies the landmarks around the breast. Then s/he loads the template model and proceeds with the matching of the template mesh onto the scan data. At this moment, the user is able to: (1) measure the volume and other surface distance of the breast, (2) obtain a model whose breast base is always visible (even when the breast is sagged) and (3) identify clearly the characteristics of the breast by comparing it with the average model, that is, exaggeration.

Also have shown is a model-based approach to accomplish correspondence among multiple scan data. Landmark locations have been used as the primary

feature to be mapped among each other. The correspondence is found by matching a template model onto each scan data, which is composed of two steps—at the first step, every vertex on the template mesh on its lower LoD is repositioned to its corresponding point's location on the scan data. At the second step, the LoD of the template mesh is converted to a higher one and direct mapping followed by relaxation is iteratively carried out.

Our template model has been designed in a way that (1) its landmark locations as well as the surface measure always remain relatively at the same location throughout any deformation. This means that we can always keep track of landmark location as well as surface measures, which is a convenient feature.

Since we are using the scans that have been measured following the measurement protocol of Lee *et al.*³, the border of the breast could be efficiently identified only using the surface data. We have shown then how we proceed with borderline to measure the volume of the breast: (1) the breast bulk is detached from the torso. (2) We fill the hole on the torso by generating functional approximation of the mesh, using RBF. (3) Then both the original mesh (before the breast bulk has been detached) and the mesh after the breast bulk has been detached and whose hole has been filled are closed by a new surface. The new surface shares the same boundary as the original mesh and is facing backwards, making each of the mesh a closed surface. (4) We finally apply the Gauss' theorem to measure the volume of each closed mesh. (5) We take the difference between the two volume values as the volume of the breast.

We have also shown the principal components of the shapes. Although the data scan could be further extended and the PCs altered depending on the data we use, they provide useful information on the shape variation that is exhibited in multiple breast shapes.

Finally, it is our hope that we extend this modeler to develop objective quantification of the beauty of the breast.

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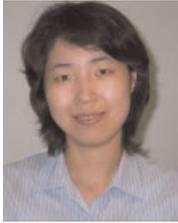
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Authors' biographies:



Hyewon Seo is an assistant professor and supervisor of the Computer Graphics Laboratory in the Department of Computer Science and Engineering at the Chungnam National University, Korea. Her research interests include imaging, visual simulation, human computer interaction, and VR. Seo has graduate degrees in computer science from the University of Geneva and KAIST. Readers may contact her at hseo@cnu.ac.kr.



Frederic Cordier is a visiting professor at the Graduate School of Culture Technology at KAIST. His research interests include 3D modeling and texturing, human computer interaction and physics-based simulation. Cordier has a Ph.D. in computer science from the University of Geneva, Switzerland. Contact him at cordier@kaist.ac.kr.



Kyunghi Hong is a professor of the Clothing Comfort Laboratory in the Department of Clothing and Textiles at the Chungnam National University, Korea. Her research interests include clothing ergonomics, sensibility ergonomics, clothing comfort and apparel technology. Hong has a Ph.D. degree in textiles from the University of Maryland. Contact her at khhong@cnu.ac.kr