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Comparative Assessment of 3D Surface Scanning Systems in Breast Plastic and Reconstructive Surgery

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Abstract

In this work, we compared accuracy, repeatability, and usability in breast surface imaging of 2 commercial surface scanning systems and a hand-held laser surface scanner prototype coupled with a patient's motion acquisition and compensation methodology. The accuracy of the scanners was assessed on an anthropomorphic phantom, and to evaluate the usability of the scanners on humans, thorax surface images of 3 volunteers were acquired. Both the intrascanner repeatability and the interscanner comparative accuracy were assessed. The results showed surface-to-surface distance errors inferior to 1 mm and to 2 mm, respectively, for the 2 commercial scanners and for the prototypical one. Moreover, comparable performances of the 3 scanners were found when used for acquiring the breast surface. On the whole, this study demonstrated that handheld laser surface scanners coupled with subject motion compensation methods lend themselves as competitive technologies for human body surface modeling.

Keywords

3D surface scanning, breast surgery, anatomical surface modeling, plastic and reconstructive surgery

Introduction

In breast plastic and reconstructive surgery, the quantitative evaluation of breast morphology has gained increasing interest for the related potentials in surgical planning and surgery outcomes assessment. In the late 1990s, several studies described methods for breast morphology quantification, including anthropomorphic distance measurements between specific body landmarks,[1,2] water displacement measurement,[3,4] molding techniques,[5] and magnetic resonance imaging (MRI).[6,7] Regardless of the specific technique, the quantitative assessment of breast volume and shape was envisioned to provide surgeons with objective measures as a way to enrich the subjective evaluation of breast aesthetics, eventually supported by uncalibrated photographs,[8-10] before and after surgery. More recently, the widespread application of 3D imaging and volumetric modeling in medicine for diagnosis and surgical planning has roused the attention of plastic and reconstructive surgeons for breast 3D modeling techniques, featuring daily applicability and providing a complete, accurate, and patient-specific morphological breast quantitative representation. In this respect, conventional breast measurement methods are not applicable. The water displacement method provides a rough estimation of breast volume but no morphological information. Molding techniques generate a coarse physical copy of the breast surface, on which accurate measurements can hardly be obtained. Imaging technologies (CT, MRI), although providing accurate 3D digital breast models, are highly expensive and image the patient in the supine or prone position, thus hindering breast morphological evaluation in the standing posture.[7]

Over the past decade, alternative solutions for swift breast 3D modeling have been explored, and surface scanners emerged as the most promising technology.[10-14] Surface scanners proposed for breast modeling were typically derived from industrial metrology[10,15-19] (i.e. the acquisition of static object surface to create virtual models for back-engineering or simulation purposes). Although they were successfully applied in surface detection and 3D reconstruction in craniomaxillofacial surgery,[20-22] the use of industry-derived surface scanning

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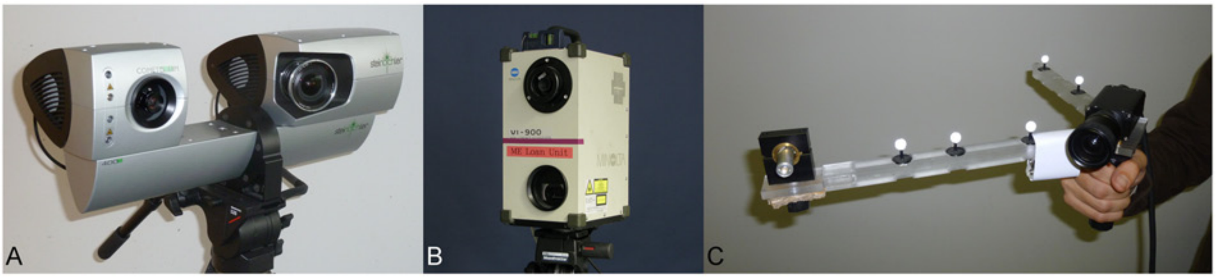

Figure 1. The 3 scanners used for this study: panel A: COMET5, Steinbichler Optotechnik GmbH, Neubeuern, Germany; panel B: Vivid 910, Konica Minolta Sensing Inc, Osaka, Japan; panel C: laser spot scanner developed at the Politecnico di Milano.

devices for digital breast modeling[10-19] faced specific issues that have hindered the achievement of a systematic clinical application of surface scanners for presurgical and postsurgical breast morphology quantitative assessment in plastic and reconstructive surgery. The main problem is related to the optical field of view of industry-derived surface scanners, which cannot acquire views of hidden areas, such as the inframammary fold and lateral rib cage portions, in a single shot. To generate a breast digital model including those body areas, multiple acquisitions with the patient and/or scanner in different positions are required.[10,15,16] This leads to unavoidable inaccuracies because of changes in the patient's posture and leads to a long postprocessing phase for stitching the surface patches generated at each acquisition, with potential operator-dependent errors affecting the final 3D model.[10,15,19] Handheld laser scanners were proposed as a way of obtaining the complete surface image within a unique long-lasting acquisition. However, the acquisition time (lasting several minutes)[23] causes large artifacts to appear on the reconstructed surface because of the patient's involuntary movements and breathing.[24] To deal with this issue, a method for patient motion compensation was proposed recently. The method relies on the contemporary 3D tracking of the handheld scanner and surface fiducials fitted on the patient[25,26] as a way to detect and compensate for the participant's motion in a frameless stereotactic approach.

In this frame, this work reports the comparative assessment of 3 surface scanners (2 fixed, industrial-derived scanners and 1 handheld scanner featuring motion compensation). The aim is to highlight potentials and drawbacks, both in terms of accuracy in 3D breast modeling and of required workload for data acquisition and postprocessing, in view of a clinical application. The selected scanners represent the 3 main technological approaches for human surface acquisition (see the Data Acquisition section): structured light projection, laser line projection, and laser spot projection. Accuracy, repeatability, and usability were evaluated by performing repeated acquisitions on a phantom and on a group of volunteers.

Methods

Test Participants

Reference acquisitions for scanner comparisons were performed on an anthropomorphic phantom of a female torso. The phantom's geometry was preliminarily captured by means of a CT scanner, featuring an image resolution of 512 × 512 pixels and a slice spacing of 1 mm. The CT scans were imported in the Amira software package (Visage Imaging Inc, San Diego, CA) for surface segmentation and the generation of the reference 3D surface model. The generated model was used as the morphological reference for evaluation of the accuracy of the scanners (see the Scanner Assessment section).

Three healthy female volunteers were enrolled in this study representing small, moderate, and large breast volumes to evaluate the accuracy of the scanners according to the most common variety of breast shapes and sizes. We therefore abandoned the option to include the patient's preoperative and postoperative 3D surface imaging in this preliminary study. The female participants showed no abnormalities in breast shape and did not undergo any surgical intervention nor did they plan to do so. All tests on volunteering participants were performed following the principles outlined in the Declaration of Helsinki and in accordance with the guidelines of the Medical Faculty at the Technische Universität München, Germany.

Data Acquisition

Three scanners were tested in this study (Figure 1): a commercial structured light scanner (COMET5, Steinbichler Optotechnik GmbH, Neubeuern, Germany: SC1), a commercial laser line scanner (Vivid 910, Konica Minolta Sensing Inc, Osaka, Japan: SC2), and a

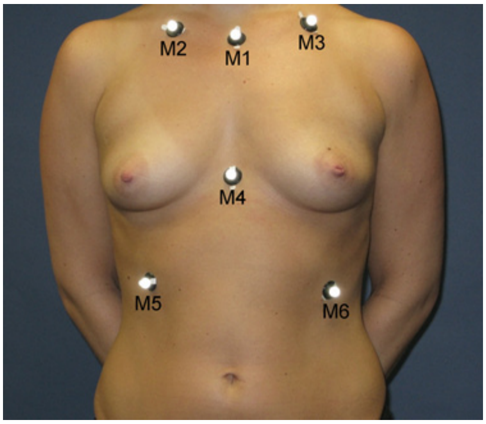

Figure 2. Passive markers configuration fitted on patient's thorax. M1: jugular lacuna; M2-M3: clavicle, at half-distance between the jugular lacuna and the acromion; M4: xiphoid process; M5-M6: medial edge of the rib cage, few centimeters above the umbilical line.

laser spot–based scanner prototype, featuring patient motion compensation[25,26] (SC3).

Each participant was scanned 3 times with each scanner (9 acquisitions in total). The phantom was rigidly positioned on a table to avoid any movement of the sample surface. The volunteers were positioned in a standing posture with both hands placed behind their body on a supporting structure (Figure 2) to limit the size of postural adjustments. The acquisition of a complete bilateral breast surface using SC1 and SC2 was performed according to the protocol proposed by Kovacs et al,[10] requiring the collection of 6 patches of the participant's surface for each acquisition: 3 from a frontal point of view (front, 45° left side, and 45° right side) and 3 placing the scanner in a lower position (front, 45° left side, 45° right side). For each acquisition (lasting a few seconds), the volunteers were asked to hold their breath.

Three single acquisitions were performed with SC3 according to the protocol described by Patete et al,[25] which followed a preliminary scanning procedure using a static programmable laser spot projector (LD2000, Pangolin Laser Systems Inc, Orlando, FL) to speed up the acquisition procedure. The static laser spot projector was programmed to scan the patient's surface with a "row-wise" pattern to acquire a dense and regular point cloud from a frontal point of view. The handheld laser scanner was then used to acquire images of the lateral thorax region and to increase the acquired point cloud density where more detail was needed. During both acquisitions, lasting about 10 minutes, participants were asked to breath normally because their respiratory movements were tracked and compensated by acquiring the motion of 6 passive markers placed on the thorax of participants (Figure 2) using the same device that tracked the handheld scanner motion.[25]

Surface Reconstruction

All 3 scanners produce 3D point clouds (i.e. a set of points defined in a 3D space - each point is defined by its *x, y*, and *z* coordinates) as the representation of the sampled surfaces. Because of the fact that scattered points in 3D space cannot be representative of a surface model, points must be triangulated to generate a continuous tiled surface. All acquired data sets were processed with a surface analysis software (Raindrop GeoMagic Studio 11, Geomagic Inc, Research Triangle Park, NC). The surfaces reconstruction was performed according to the following procedure:

1. Triangulation of each acquired point cloud
2. Smoothing of the triangulated surfaces (half of the range proposed by the software)
3. Filling of surface holes
4. Registration and merging of the surface patches (required for SC1 and SC2)

Each scanner generated 3 surface models for each participant. In addition, an "average surface model" was obtained by merging and averaging the 3 patient-specific surfaces data set to create a model that was considered representative of the scanner's performance in modeling each specific participant.

Scanner Assessment

For the comparative evaluation of the selected scanners, accuracy, repeatability, and usability were the issues that were investigated, in terms of a potential clinical application.

Accuracy. Scanner accuracy was assessed by calculating the root mean square error (RMSE) of the surface-to-surface distance between the average acquired surface of the anthropomorphic phantom and the corresponding CT-derived reference model. The surface-to-surface distance was calculated by tracing the normal to each triangular tile from the tassel centroid to the second surface. The distance was measured between the tile centroid belonging to the first surface and the intersection point (if existing) of the normal to the second surface. The overall surface-to-surface distance was obtained as the RMSE of the distribution of the obtained distances.

Repeatability. An additional test was performed to assess scanner repeatability. In this case, the RMSE of the distances among the 3 acquisitions performed on each participant was calculated. Given the lack of a CT and/or MRI derived reference model, the scanner featuring the highest

Table 1. Repeatability and Accuracy of Scanners on Phantom Acquisitions.

RMSE [mm]	SC1	SC2	SC3
Repeatability			
1 vs 2	0.298	0.398	1.856
1 vs 3	0.291	0.407	1.619
2 vs 3	0.300	0.414	1.663
Accuracy			
Average vs CT	0.562	0.748	2.018

Abbreviations: RMSE, root mean square error; SC1, commercial structured light scanner; SC2, commercial laser line scanner; SC3, laser spot–based scanner prototype, featuring patient motion compensation.

repeatability (on participants, repeated acquisitions) was used as reference for assessing the interscanner differences among intraparticipant breast digital models.

Usability. Scanner performances were also qualitatively evaluated, in terms of swiftness of the data acquisition, comfort (for both participant and operator), surface post-process complexity, reconstructed surface completeness, and data set dimensions.

The Wilcoxon rank-sum test was performed to test statistically significant differences among the quantitative indices related to accuracy and repeatability.

Results

Intradevice Accuracy and Repeatability Assessment

Table 1 reports the results concerning the comparative assessment of the examined scanners on phantom data. Accuracy was quantified using the CT scans as the reference method. Mean ± standard deviation of scanner repeatability among different phantom acquisitions was 0.296 ± 0.005 mm, 0.406 ± 0.008 mm, and 1.703 ± 0.12 mm for SC1, SC2, and SC3, respectively. The RMSE calculation for the scanner data comparisons with respect to CT scans gave values of 0.562, 0.748, and 2.012 mm for SC1, SC2, and SC3, respectively ($P < .001$)

Tables 2 to 4 show repeatability and accuracy results for the participant data. Systematic worse performances ($P < .001$) were found in this case for SC1 with respect to SC2, as clearly evident in Tables 2, 3, and 4. According to the results obtained for repeatability on the phantom and participants, the scanner SC2 was selected as reference for successive comparative assessments. Scanner SC3 turned out to feature higher repeatability with respect to SC1 in 2 out of 3 participants ($P < .001$).

When comparing SC1 and SC3 accuracies in breast morphology description, using SC2 data as reference,

Table 2. Repeatability and Accuracy of Scanners on Acquisitions From Participant 1.[a]

RMSE [mm]	SC1	SC2	SC3
Repeatability			
1 vs 2	5.723	0.942	4.009
1 vs 3	5.408	1.352	4.031
2 vs 3	2.901	1.424	4.531
Mean ± Standard deviation	4.677 ± 1.546	1.239 ± 0.260	4.190 ± 0.295
Accuracy			
Average vs reference	2.601	—	5.221

Abbreviations: RMSE, root mean square error; SC1, commercial structured light scanner; SC2, commercial laser line scanner; SC3, laser spot–based scanner prototype, featuring patient motion compensation.

[a] For accuracy assessment, the most repeatable scanner (SC2) was used as reference.

Table 3. Repeatability and Accuracy of Scanners on Acquisitions From Participant 2.[a]

RMSE [mm]	SC1	SC2	SC3
Repeatability			
1 vs 2	2.100	0.997	3.932
1 vs 3	2.279	1.729	3.497
2 vs 3	1.574	1.384	2.725
Mean ± Standard deviation	1.984 ± 0.366	1.370 ± 0.366	3.384 ± 0.611
Accuracy			
Average vs reference	2.266	—	2.464

Abbreviations: RMSE, root mean square error; SC1, commercial structured light scanner; SC2, commercial laser line scanner; SC3, laser spot–based scanner prototype, featuring patient motion compensation.

[a] For accuracy assessment, the most repeatable scanner (SC2) was used as reference.

Table 4. Repeatability and Accuracy of Scanners on Acquisitions From Participant 3.[a]

RMSE [mm]	SC1	SC2	SC3
Repeatability			
1 vs 2	2.916	2.336	2.489
1 vs 3	3.128	2.214	2.689
2 vs 3	2.929	1.085	2.377
Mean ± Standard deviation	2.991 ± 0.119	1.878 ± 0.690	2.518 ± 0.158
Accuracy			
Average vs reference	3.986	—	3.276

Abbreviations: RMSE, root mean square error; SC1, commercial structured light scanner; SC2, commercial laser line scanner; SC3, laser spot–based scanner prototype, featuring patient motion compensation.

[a] For accuracy assessment, the most repeatable scanner (SC2) was used as reference.

Figure 3. Phantom's and participants' reconstructed surfaces: first column, pictures of the phantom/participants; second column, surfaces reconstructed with SC1; third column, surfaces reconstructed with SC2; fourth column, surfaces reconstructed with SC3.

comparable results were found. SC3 featured performance similar to SC1. Altogether, SC1 and SC3 fared noticeably worse than SC2.

Breast Models Assessment

Figure 3 reports an exemplifying case of breast digital models generated by the 3 scanners. Evident differences are noticeable. In all cases, the scanners were able to generate models of the complete thorax of the participant. SC3 exhibits lower performances in the level of detail of breast description with respect to the commercial scanners. On the other hand, the effects of participants' motion compensation in removing the breathing artifacts on the reconstructed surface appear evident.

SC1 and SC2 required 3 to 5 s for the acquisition of each surface patch, with a total time of approximately 5 minutes for both SC1 and SC2, for the acquisition of the 6 patches including the time required for patient and scanner repositioning. Conversely, SC3 acquisition required approximately 1.5 minutes for the initial automatic programmed frontal scanning and a time varying from 5 to 10 minutes for the handheld scanning phase. It is worth recalling that from the operational point of view, ensuring the visibility to the 2 TV cameras of the optical tracker of the fiducials placed on the handheld laser scanning structure and on the patient was not trivial, requiring specific skills to the operator. The postprocessing phase was less demanding for SC3 acquisitions with respect to SC1 and SC2. In these latter cases, the registration and stitching of the 6 acquired surface patches required specific operator skills in computer graphics.

Discussion

The reported analysis on scanner accuracy and repeatability proved that industry-derived surface scanners, designed for accurate measurements, feature high accuracy when a static object (the phantom in this case) is modeled. The differences between our results and the nominal accuracy specified by the constructor of SC1 and SC2 (0.001 and 0.01 mm, respectively) are mainly imputable to inaccuracies introduced in the postprocessing phase (data smoothing, surface patch stitching, and merging). Poorer performances in static measurements from SC3 were largely expected because of the lower intrinsic accuracy of the optical device used for handheld laser tracking, especially in a large working volume as the one required for experimental acquisitions. As a whole, accuracy evaluation for SC3 confirmed the values reported in Patete et al.[25]

The assessment of scanner functionality in experimental acquisitions on participants helped pinpoint critical issues for SC1. The problem is that the SC1 acquisition process is organized as a repeated projection of a fringe pattern that progressively increases its density in about 5 s. This is the period during which the thoracic surface exposed to the projector is acquired; involuntary motion by the patient (including breathing movements) in this active scanning period cause major artifacts on the reconstructed surface; in some cases, we were forced to repeat the acquisition because of completely unsatisfactory outcomes.

For SC2, only 3 s were required for a complete scanning resulting in less motion-related artifacts on the reconstructed surface. Despite a much lower accuracy and more complex setup and calibration procedures, SC3 turned out to exhibit some advantages with respect to commercial static scanners, when participant images were acquired. Although the price to be paid was a long acquisition time, the generation of a unique digital model reduced the postacquisition process to a simple wrapping of the point cloud in a mesh and a filter, with no patch stitching procedures. Moreover, this scanner yields almost constant accuracy in the whole working volume, which is determined by the intrinsic accuracy of the tracking system and the calibration procedures, thus independent by the position of the participant within the useful acquisition volume.

In terms of clinical applicability, SC1 and SC2 force the participants to hold their breath during the acquisition time of a few seconds. This might represent a critical issue, especially with poorly compliant patients. Lower constraints are imposed by SC3 on the participant, but it needs a well-trained operator for performing optimal system calibration and optimizing scanner use. The cumbersome architecture of SC1 and SC2 are obstacles to their handy installation in the complex environment of a surgical room. Conversely, SC3 features a modular architecture inherited from surgical navigation systems and is, thus, well suited for installation in surgical rooms and intraoperative operations.

Conclusions

The need for quantitative tools for the acquisition of breast morphological images is increasing in breast plastic and reconstructive surgery. The reference technology in this field is based nowadays on surface scanning systems developed for industrial metrology, which are designed for coping with moving objects.

In this study, we reported the results of the comparison among 2 common commercial surface scanners, which have been used in several studies for breast surface modeling in plastic and reconstructive surgery, and a laser spot–based scanner prototype coupled with participant motion detection and compensation.

The commercial scanners confirmed high accuracy in acquiring static surfaces but showed some weaknesses when acquiring breast surfaces in live participants. The main advantage of the portable scanning prototype is related to the compensation of participant motion in the frame of a long acquisition time. The resulting unique model enables swift data postprocessing, avoiding the stitching of multiple patches, as is required for static scanners. Although new generations of 3D imaging systems are able to capture the breast surface in a single shot combining multiple cameras or mirror constructions, the trade-off between surface completeness and the participant's motion management remains a challenging issue. According to our results, there is room for a competitive role for handheld laser scanners in breast quantitative modeling, which is, however, tightly linked to swift and fast acquisition modalities based on laser line scanning coupled with robust methods for online participant motion compensation in the frame of low-cost commercial products.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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