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The Vasculens - Projector-Based Augmented Reality Display of Anatomical Structures Segmented from Pre-Operative CT Scans

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Abstract— **Augmented reality technologies can improve surgical navigation. These augmented reality technologies promise to improve both the safety and efficiency of operations. The Vasculens is a novel handsfree and focus free projector-based augmented reality system that works by projecting segmented preoperative CT scan data directly onto a patient. The Vasculens is designed to help surgeons visualize vascular anatomy during free flap harvesting surgeries. One example of a free flap is a deep inferior epigastric perforator (DIEP) flap that is harvested to create a new breast mound after mastectomy.**

This paper reports the reprojection accuracy of the Vasculens. In brief, 25 metal fiducials were placed on the torso of a life-sized mannequin, the mannequins were scanned in a CT scanner, the metal fiducials were segmented, and the Vasculens was used to project the expected location of the metal fiducials onto the mannequins. The reprojection accuracy was defined as the mean of the absolute distance between the location of the metal fiducial and the projected fiducial location. The mean reprojection error for the female mannequin was 0.6 mm for the male mannequin was 0.2 mm. These accuracy results support the conclusion that the Vasculens is a promising technology for improving DIEP flap breast reconstruction surgery and other free flap surgeries.

Keywords— **Augmented reality, vascular anatomy, intraoperative, DIEP flap harvest, mixed reality**

I. Introduction

This paper is a continuation of the work that was previously published and presented at the Clinical and Biomedical Engineering Conference in 2021 [1]. That paper included a description of the Vasculens, a novel handsfree and focus free projector-based augmented reality system. Furthermore, the reprojection error for the Vasculens was described and reported. In this paper, the Vasculens is largely the same. The main difference in this work, compared to the prior work [1], is that CT scan data was collected and the testing of the Vasculens was done in a manner that more realistically reproduces the clinical workflow that the Vasculens will ultimately be used in. This paper is best read in conjunction with the prior publication [1].

The clinical motivation for developing the Vasculens is to improve breast cancer patient. Following a mastectomy, breast cancer patients commonly undergo breast reconstruction. Autologous breast reconstruction (flaps) is often done using the deep inferior epigastric perforator flap (DIEP). This surgery includes harvesting fat in the abdomen (supplied by perforators of the deep inferior epigastric artery and vein (DIEA/V) and then using the abdominal fat to create a breast mound with vascular supply from the internal mammary artery and vein (IMA/V) under the costal cartilages of chest.

The most challenging part of this surgery is the dissection of each perforator from the surrounding rectus abdominis muscle. To do this step, the surgeon must estimate the trajectory and orientation of the perforator vessels and inferior epigastric artery as they run through and underneath the rectus abdominus muscle.

A CT angiogram scan is often done preoperatively to identify the location of each perforator artery as it pierces through the rectus fascia. The surgeon then uses the information from the CT angiogram to draw the location of the perforator arteries onto the patient (Figure 1). The error in drawing such markings is approximately 1 mm [2]. Thus, 1 mm is considered an accepted reprojection error for DIEP surgical guidance.

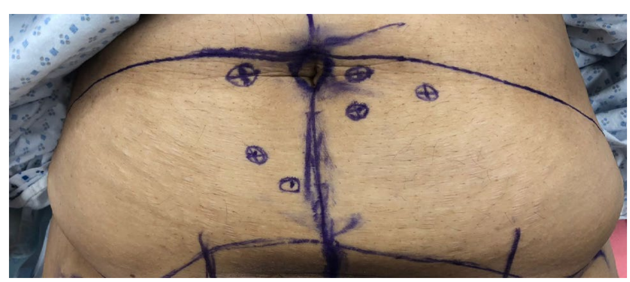


Figure 1: Picture of patient's abdomen prior to DIEP flap surgery. The crosses mark the locations of the DIEP arteries.

There has been successful use of AR navigation guidance systems for urological [3, 4], extremity surgery [5], and DIEP flap breast reconstruction. [6, 7]. Notably, the Microsoft HoloLens augmented reality glasses has even been used for preoperative DIEP guidance [6]. Another group used a camera and handheld projector to project DIEP arteries and their intramuscular trajectories onto patients and tested in a randomized, open, single-center, superiority trial with 60 patients undergoing DIEP flap breast reconstruction [7].

One of the main advantages of the Vasculens, when compared to the systems described above, is its simplicity. To use it, just a few clicks on marks on the surgical field are required, and then the projected image appears. Ultimately, the motivation for developing the Vasculens is to reduce operative times and complication rates for DIEP flap surgeries.

II. Methods

A) *Materials*

The VascuLens system includes the following hardware components: 1) Two life sized mannequins, 2) Fifty metal fiducials markers (Nipple Marker X-SPOT® 1.5 mm Lead-free Metallic Pellet NonSterile by McKesson), 3) CT Revolution GE Scanner, 4) PicoPro laser projector (Cellulon, Seoul, Korea) with 1920 x 720p resolution and brightness of 32 lumens, 5) a mounting arm for holding the projector above the surgical scene, which for the experiments in this paper is a 360° rotating mount bracket cantilever phone holder, 6) a laptop computer which can run the software and connect to the projector via HDMI cable, 7) digital calipers.
The VascuLens system's main software components are: 1) ITK-SNAP, an open-source software distributed under the GNU General Public License 2) the console application (C++ and OpenCV), and 3) OBS Studio, a third-party program which connects the console application to the projector.

B) *Clinical and technical workflow of VascuLens*

The proposed workflow of the VascuLens system was previous described in detail. In brief, the steps are as follows:

Step 1 - Generating the initial source image (P_{src}) from the preoperative CT scan
ITK-Snap is used to view the CT scan and segment the anatomy of interest. In the clinical setting, the DIEP arteries would be segmented, in this case it was the metal fiducials that were segmented. Next, the initial projector image (P_{src}) is generated by capturing a 2D image of the segmented anatomy, from a virtual camera that is positioned 1.5 m above the umbilicus.

Step 2 - Registration to generate the distorted destination projector image (P_{dst}) :
Four registration points are either drawn or placed (metal fiducials) onto the patient. These registration points correspond to the location of four metal fiducials placed onto the patient's skin just prior to the CT scan and segmented during step 1. The VascuLens projector is placed above the patient's umbilicus and the four registration points ($x_i'$and y_i') are selected with laser projected computer cursor ($x_i$and y_i). These points are at identifiable locations that relate to the perforator arteries. As shown in equation 1, these four corresponding points are then used to calculate the scaling factor (t_i) and the 3x3 mapping matrix M by Gaussian elimination via the OpenCV *getPerspectiveTransform* function.

$$\begin{bmatrix} t_i x_i' \\ t_i y_i' \\ t_i \end{bmatrix} = M \cdot \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} \qquad (1)$$

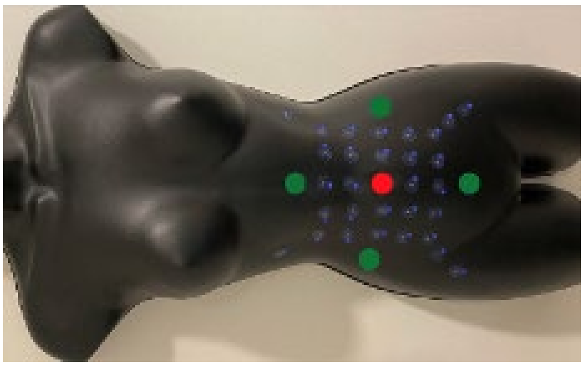
Next, the OpenCV *warpPerspective* function [7] and the 3 x 3 matrix M are used to transform (translation, rotation, scaling, shear, reflection) P_{src} into P_{dst}. This is shown in Eqn. 2. and the final projection of P_{dst} onto the patient or mannequin is shown in Figure 4.

$$P_{dst}\ (x, y) = P_{src}\left(\frac{M_{11}x + M_{12}y + M_{13}}{M_{31}x + M_{32}y + M_{33}}, \frac{M_{21}x + M_{22}y + M_{23}}{M_{31}x + M_{32}y + M_{33}}\right) \qquad (2)$$

Step 3 - Intraoperative guidance:
With P_{dst} continuously projected onto the patient, a permanent marker is used to trace the projected marking onto the patient. These markings show the location and course of relevant vascular anatomy. During the operation, the surgeon uses these skin markings to help him/her plan the skin incision, locate the perforator arteries, and proceed with the 6-8 cm intramuscular DIE arteries.

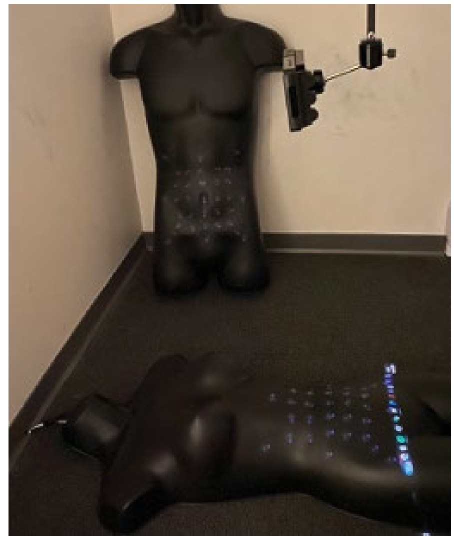
C) Experimental Data Collection

As described previously, the metal fiducials were placed on the torso of two life-sized mannequins. The registration fiducial markers were placed were placed 10 cm superior to the umbilicus, 10-12 cm to the left and right (along the axial plane) of the umbilicus and 10 cm inferior to the umbilicus. The 25 experimental fiducial markers were placed in a grid, centered on the umbilicus, with a distance of approximately 3cm between each fiducial.



Next, the mannequins were scanned in the CT Revolution GE scanner.

After the CT scan, the segmentation of the fiducial markers was done with ITK-SNAP, the source image (P_{src}) was created, followed by registration to create and project the distorted destination projector image (P_{dst}). Then the estimated location of the metal fiducials was projected onto the mannequin.



The reprojection error is analogous to the reprojection error that would exist between the projected and actual vascular anatomy after the subcutaneous fat has been dissected away. The reprojection error is the absolute distance between the center of the 1.5mm metal fiducial and the center of the 1.5 mm projected point The reprojection error was measured using a digital caliper with accuracy to a tenth of a millimeter. The projected points represent the estimated location of the fiducials. For each mannequin, 25 saddle points were measured as a sample of all the points that could be marked on the surface of the body form.

III. RESULTS

The reprojection error for each metal fiducial on each mannequin are shown in Table 1 and 2 below.

Table 1: Reprojection error (mm) for the female mannequin. Each entry in the table corresponds to the reprojection error for an individual metal fiducial. The table maps, in a 1-1 spatial manner to the fiducials as they were placed on the mannequin, from the perspective of someone looking down at the mannequin. The middle cell in the table (***0***) corresponds to the metal fiducial that was placed on the umbilicus.

1.3	0	0	0	2.1
0	0	0	0	0

0	0	***0***	0	0
0	1.4	1.8	2.1	0
0	1.3	1.4	2.0	1.5

Table 2: Reprojection error (mm) for the male mannequin. See the description in Table 1 to understand the data shown in this table.

0	0	0	2.0	3.1
0	0	0	0	0
0	0	***0***	0	0
0	0	0	0	0
0	0	0	0	0

The mean reprojection error for the female mannequin was 0.6 mm the male mannequin was 0.2mm.

IV. Discussion and Future Work

In general, the peripheral points had the largest reprojection error. Beyond that observation, there was no consistent spatial pattern for the reprojection error. Furthermore, it is difficult to explain why the different mannequins had a different rate of error. It may have been due to variations in the segmentation or accidental movement of the projector or mannequin during the experiment. Notably, patient breathing was not simulated in these experiments. In patients, we anticipate that there will not be significant lower abdominal movement with normal respiration.

Furthermore, the mean reprojection error of 0.6 and 0.2 mm is less that the mean reprojection error of 1.7 mm that was previously reported for the Vasculens system [1]. This improvement is likely because the mannequin was scanned with a highly calibrated CT scan system as opposed to having a CT scan simulated via a photo of the mannequin. The maximal reprojection error was 3.1mm on the male mannequin and 2.1 mm on the female mannequin. In a surgical context, this could lead to inaccurate dissections. However, the maximal errors were at the outer bounds of the reprojection box and in most cases the inferior epigastric artery will be closer to the midline where there was smaller error. Furthermore, consultation with surgeons to understand the requirements for mean and maximal reprojection error is required. The differences in error between the two mannequins is likely due to variations in segmentation and experimental setup.

A sub-mm mean reprojection accuracy is appropriately small for use in the clinical setting. However, additional challenges in the clinical setting will be that the patient has subcutaneous fat. Adjusting the virtual position of the camera prior to creating the the initial source image (P_{src}) may be a way to manually adjust for the subcutaneous fat and have an accurate represent to the location of the perforators and intermuscular course of the perforators drawn onto the skin of the patient. Furthermore, it has generally been observed that the thickness of subcutaneous abdominal fat is fairly consistent across the entire abdomen.

Future work will include clinical testing with actual patients where the reprojection error for the actual perforator arteries is reported. Patient movement and flap movement when the flap has almost been separated from the abdominal muscles will have to be assessed and characterized.

V. Conclusion

In conclusion, the Vasculens system is a novel proof-of-concept handsfree surgeon-in-the-loop augmented reality guidance system for DIEP flap breast reconstruction surgery. It is simple, requires only a few clicks on marks on the surgical field to operate and a submillimeter reprojection error when a CT scanner is used to scan a mannequin with metal fiducials on it.

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