USING VISUALIZATION AND MODELLING TO IMPROVE PRE-SURGICAL DECISION-MAKING IN BREAST RECONSTRUCTION SURGERY

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Abstract

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A mastectomy surgery is the removal of breast tissue in an operation, typically as a treatment or a method of prevention for breast cancer. The loss of breasts can have a negative impact on the patient's body image, therefore in some cases a reconstruction surgery is done in order to restore the lost shape and volume with the use of silicone breast implants. In cases where only one breast is removed, retrieving the lost symmetry is also of high importance. Unfortunately, over 20% of the cases do not end up with a satisfying result. [1]

In this dissertation, we first studied the use of augmented reality (AR) in surgery planning before reconstruction surgery. To do this we developed an app for Microsoft HoloLens that allows the users to go through implant models as AR objects. In a preliminary study we assessed the usefulness of AR for decision making, as well as users' abilities to adapt to the AR environment.

In addition, we investigated the potential of using FEM to model breast and implant deformation to improve the decision making process in reconstruction surgery. In order to do this, we designed a system that can choose the best match in terms of shape for the patient based on 3D models generated from pre-surgery MR images. A user study with 7 users was performed to assess the choices made by the proposed system and determine if it is capable of making the same decisions as human users.

The results of our experiments show the effectiveness of AR, as well as the potential of our proposed system, in improving the efficiency of the decision making process. AR is capable of providing better visualization, while our system is able to decrease the number of options that need to be considered when planning for reconstruction surgery.

The results of this thesis suggest that computerized decision making tools in breast reconstruction surgery can improve clinical decision making, as well as reduce costs associated in this surgery.

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Special thanks to my family members and friends, for the encouragements, advises, and for being my light house when the sea was stormy.

This dissertation is dedicated to the loving memory of my late mother, who passed away from cancer and was the reason I started to have an interest in the medical technology field. I wish you could read this, and I hope that I have made you proud.

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Chapter 1

Introduction

In 2020, more than 2 million new patients were diagnosed with breast cancer, making it the most common type of cancer in women [2]. Treatment options for breast cancer include: chemotherapy, radiotherapy, breast-conserving surgery and mastectomy, i.e. complete removal of breast tissue. Mastectomy surgery is recommended to women with a family history of breast cancer to prevent cancer (i.e. prophylactic mastectomy), to patients who have re-occurring cancer in the same breast, or in cases where breast-conserving surgery is not a feasible option [3]. According to the National Cancer Database (NCDB), in 2018 more than 100,000 patients had a total mastectomy in the US alone [4]. Of these patients, many decide to have reconstruction surgery to recreate the lost shape and volume of their breast using a breast implant. In this procedure, usually a breast implant is used, which is a silicone pocket that is filled with either silicone gel or saline. There are a variety of implants available in different sizes and shapes, and the surgeon and the patient agree on the implant to be used in a pre-surgery decision making process.

The appearance of the final result is a key concern to the patients who undergo reconstructive surgery. In particular, in cases where only one breast is removed (a single mastectomy). The symmetry of the natural and modified breast is crucial to the patient, however, in can be difficult for the surgeon to achieve. Due to the lack of measurement and surgical planning tools, the decision about the shape and size of the implant is made by visually; the surgeon chooses between tens of available implants to find the one that can reproduce the correct symmetry between the patient's breasts. Dissatisfaction with the result of the surgery can lead to additional surgeries, where the surgeon will try to modify the size and shape of the breast to increase the patient's satisfaction and well-being. A study from in 2016 showed that more than 20% of reconstructions done immediately after mastectomy do not satisfy the patient, leading to a second (revision) surgery to fix the undesirable results of the first one [1].

In the following dissertation, we explore the potential of using breast and implant modelling and augmented reality (AR) to improve the decision-making process in breast reconstructive surgery after mastectomy. Furthermore, we address the shortcomings related to the choice of implants in pre-surgery decision making, by comparing 3D generated models of patients' breasts to 3D models of implants, and suggesting the best implant choices for each patient. The patient models were generated based on MRI images taken before a surgical intervention. Our system takes advantage of FEM to simulate the shape of both the breast and the implant with the impact of gravity in standing position and uses Hausdorff distance as the measure of similarity.

1.1 Augmented Reality in Breast Reconstruction Surgery

Augmented reality (AR) is the fusion of computer generated virtual elements with the real-world environment. AR can be used to enhance our understanding of the environment around us by visualizing new information or highlighting what is already there. In surgical planning, AR can be useful by providing 3D visualization of the anatomy and surgical plans, or even simulating the outcome of the surgery beforehand. In the case of breast reconstruction, using AR to visualize the result of the surgery can be beneficial for choosing the right implant for the patient. By showing the result that is gained by using each of the available implants, it can help both the surgeon and the patient choose the implant that can create the desired shape and volume. This can help in pre-operative planning by demonstrating the result that can be achieved by using each implant within the context of the patient's body, and without the need for sizers of physical implants. In the first part of this thesis, our goal was to determine if the users find an AR system for surgery planning useful and easy to work with, and to see if they can recognize slight differences in implant shapes as AR objects (see Figure 1).

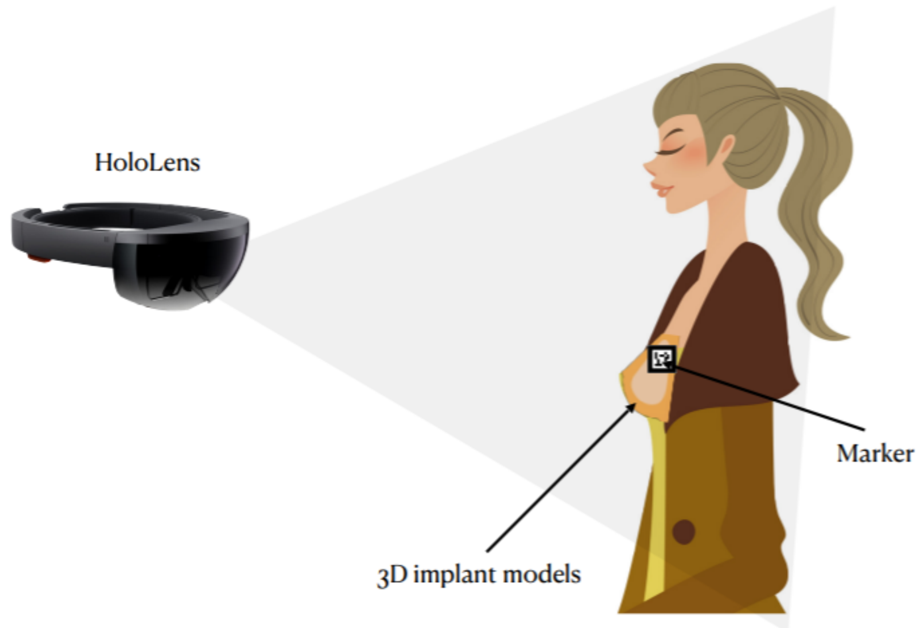

Figure 1: Overview of the developed Hololens AR system for breast implant selection. The surgeon would wear a head mounted display (HMD) and be able to compare different implant sizes within the context of the patient anatomy.

1.2 3D Modeling in Breast Reconstruction Surgery

Finite Element Method (FEM) is a technique that is used to simulate the behavior of a physical system, such as the deformation of a material affected by external or internal forces. FEM is used to solve complicated problems by dividing them into smaller pieces and calculating an estimation of the final answer. FEM has been used in surgical planning to predict the shape or position of the target anatomy based on the medical images taken prior to surgery. By using this technique, pre-operative images obtained can be used to simulate the final result of the surgery thus helping with the surgical planning decision making process.

1.3 Thesis Contribution

As part of this research, we studied the use of augmented reality (AR) in pre-operative planning, as well as the use of finite element modeling (FEM) as tools for pre-surgical planning to choose the best implant model in breast reconstruction surgery. In order

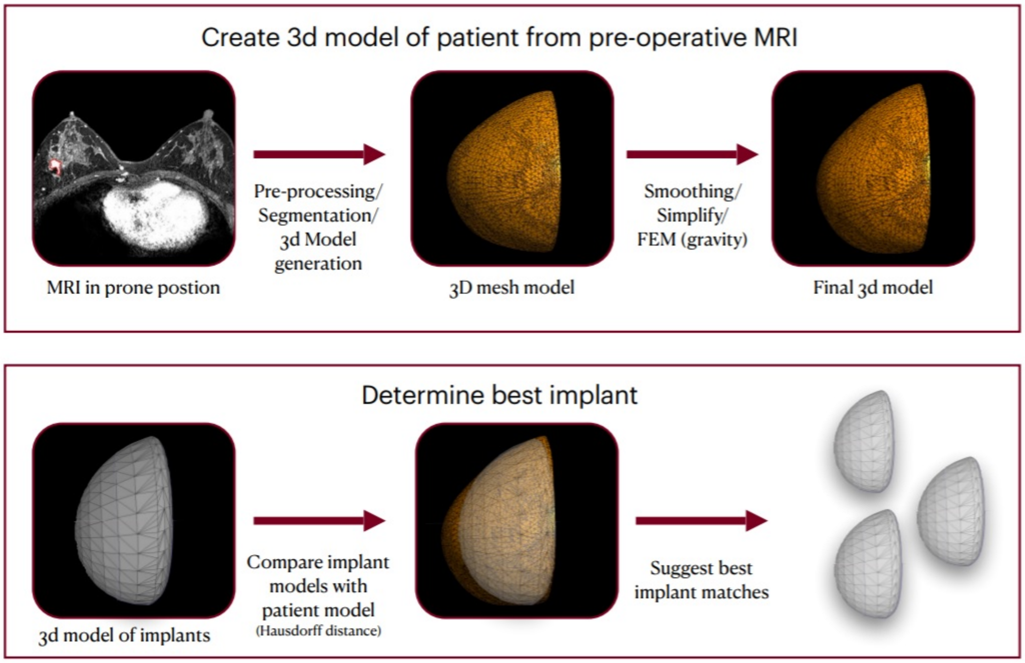

Figure 2: An overview of the processing pipepline to determine the best implant. A 3D model of the patient is created using pre-operative images and after FEM is used to determine the best implants.

to study the use of AR in the process of decision making before surgery, we developed an AR application for the Microsoft HoloLens that allowed for the visualization of different implants on the patient. For the purpose of exploring the use of FEM in this process, we developed a system that can simulate the deformation of breast from pre-operative MRI scans and compare the 3D models to available breast implant models to suggest the best choice of implant for the patient. In both cases, a user study was performed to determine in the case of AR, the usability of our proposed solution from the users' point of view, and in the case of suggesting the best implant, the suggestion from the system compared to users' choices.

The results of the study regarding our AR app with 13 participants indicated that:

1. Users found the idea of using AR for comparing models to real world objects useful and were able to adapt to the AR user interface without any issues.

2. As HMDs are not a commonly used device and unfamiliar for many, there was a learning curve that the users had to overcome. Compared to other daily used technology devices, the Microsoft HoloLens interface was determined to

be tiring.

3. The use of a more common device capable of executing AR applications, such as a smartphone or tablet, would be preferred by the users.

The results of our study on the use of FEM for suggesting the best choices of implant showed that:

1. The suggested system is able to make similar choices to human users, in a more efficient way.

2. By limiting the number of implants the surgeon must go through in decision making, the process can be easier and more accurate.

1.4 Organization

The remainder of the thesis is organized as follows. We begin by providing background information of the definition of AR, as well as the use of AR in surgical planning in Chapter 1. We also introduce FEM and the benefits of using it in pre-operative decision making as well as during the operation. In this chapter, previous publications related to the use of FEM and AR for surgery and commercial examples of it are reviewed. In Chapter 3, we present an experiment involving the use of a head-mounted device-based AR application for pre-surgical decision making. This chapter includes a presentation of a developed application for the Microsoft HoloLens, and the results of a user study that was conducted to determine the usefulness of the aforementioned application. Chapter 4 presents a system to assist the surgeon in choosing the implant for the patient, with the help of FEM. We begin by defining the system and its workflow. Then a user study is described, which goal was to determine if the system is capable of choosing the same implants as human subjects. Lastly, we summarize the results of the study. Chapter 5 concludes the thesis and discusses potential future improvements to the developed systems.

Chapter 2

Background

In this chapter, we first explain how Augmented Reality (AR) can be used in surgical planning and describe research and commercial systems in the area of augmented reality in breast reconstruction planning and surgery. Then, in Section 2.2, we introduce the Finite Element Method (FEM) and review related work on the use of FEM in breast reconstruction and mastectomy planning.

2.1 Surgical Augmented Reality

Augmented reality (AR) is an experience where parts of the real world environment are enhanced with computer-generated virtual elements. These virtual elements are merged within the real world and can respond to changes in the user's environment in real-time [5]. AR can be markerbased, meaning the position of the augmented object will be calculated using a pre-defined pattern or even an object that is available in the real world. It can also be markerless, and the position of the virtual objects can either be calculated using sensors that scan the environment to determine the place and position of the virtual objects, or be assigned by the application, independent from the surrounding environment, only based on the position of the camera.

In contrast to virtual reality (VR), which provides a complete immersive experience, in AR the computer-generated components are designed in a way that they overlay the real world, instead of replacing it. Another term that will be used in this paper is mixed reality (MR), which can be defined with the help of a virtuality continuum (see Figure 3). This continuum represents the different levels at which

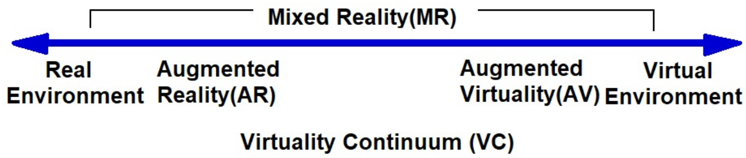

Figure 3: Simple representation of a virtuality continuum as defied by *et. al* [5]

virtual and real objects or environments are merged together. At one end of this spectrum there is a purely virtual environment (with no real world elements) and at the other end stands the real environment, which means no virtual object is included in the environment and only real objects are present. Milgram *et. al* [5] defined mixed reality to be any environment that can be placed somewhere between these two extremes.

2.1.1 Augmented Reality in Surgical Planning and Interventions

It is important to have accurate and detailed knowledge of the surgical anatomy prior to the intervention. For this reason, both augmented and virtual reality have been explored in the context of surgical interventions. Specifically, augmented reality can be used to visualize anatomical structures, project the data onto the patient's body, and provide a better understanding of the anatomy of interest pre-operatively, intra-operatively and and post-operatively [6]. Vles *et al.* [7] suggested that using AR for surgical planning and during an operation can increase accuracy, decrease time spent on each surgery, and thus has the potential to decrease complications. In the following section, we summarize a number of papers focusing on AR in surgical planning, however, the interested reader can refer to Yoon *et al.* [8] and Vles *et al.* [7] for a more comprehensive review of mixed reality in surgery.

Fushima and Kobayashi [9] used mixed reality for surgical planning in the context of maxillofacial surgery, i.e. surgery to correct deformity of jaw bones and teeth. The authors used a patient's 3D computed tomography (CT) scan to construct both a 3D model o and a dental cast model of the patient's skull and jaw bones. These two models are integrated by putting a reference splint (3 titanium spheres fixed on an acrylic plate) between the teeth of the 3D dental model while taking the CT images. The spheres can then be detected in the images as landmarks, and used

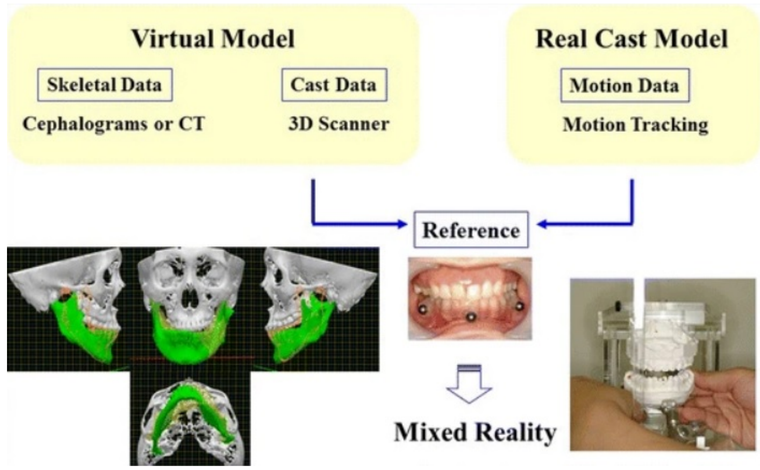

Figure 4: Mixed reality surgical simulation system for maxillofacial surgery, introduced by Fushima and Kobayashi [9].

to register the two models. The virtual model is also used to diagnose and assess asymmetries in the dental and bone structure, before starting the simulation. Fushima and Kobayashi [9]'s system uses mixed reality to simulate the result of the surgery by integrating the 3D virtual model with the dental cast model. Using the three spheres as reference points, the virtual model can replicate the movement of the 3D cast model in real time. Corresponding changes in the skeletal structure are simulated based on these movements and shown on a PC monitor, while occlusal changes are evaluated based on the virtual model of the case on the simulator. Thus, by changing the position of the jaws on the real cast, the operator is able to simulate the jaw bones in the 3D model. (See Figure 4)

The system was tested on two patients with both skeletal and dental asymmetries, and the accuracy of both their tracking system and their simulation was deemed sufficient for clinical use. The measurement error of the whole simulation was less than 0.32mm. However, as the system prefers facial symmetry over dental, further orthodontic treatments were needed to fix the position of the teeth as well.

Pratt *et al.* [10] developed an AR application using the Microsoft HoloLens [11] for planning and intervention of vascular pedunculated flaps of the lower extremities. In a flap surgery, healthy tissue (flap) is taken from a location from the body in order to cover another part that has lost skin, fat, and/or muscle. A vessel from the receiving site is taken and connected to the flap in order to feed it and keep it alive. In Pratt *et al.*'s work, the patient is scanned using a contrast-enhanced computed tomography angiography (CTA) in the prone position (to limit tissue deformation of the soft tissue of the leg and compression of the vessels). The CTA volumes are segmented into skin, bone, muscle and vasculature and the resulting 3D models are overlaid onto the patient using the developed HoloLens application. The user can interact with the virtual models by rotating, moving and scaling using hand gestures and voice commands, until the model and anatomical landmarks on the patient's body align to a reasonable degree. During planning, the AR application allows the surgeon to "see through" the patient's body, mark the position of the perforators, and select the ones that can potentially be used during surgery. The application can also be used during the surgery for guidance. The developed pipeline takes on the order of 30 mins: 5 minutes for scanning the patient(CTA), 10-20 minutes for segmentation, 20-30 minutes for preparing and processing the mesh model, and less than a minute for uploading and configuring the HoloLens, and 1-2 minutes for manual registration of the model and the patient. The system was tested on 5 clinical cases (see Figure refpratt-flap), where the authors compared the identification of the position of perforators using the HoloLens overlay to the traditional method of using Doppler ultrasound. Although in some cases deformation of soft tissue caused 1-2 cm of discrepancy in the position of the perforator in the AR application and the surgical finding, the surgeons found the system reliable and less time consuming than the Doppler method. Drawbacks that were mentioned, was that the system requires the presence of a technical assistant to help with data preparation before surgery, as the processing of the images and the mesh needs manual involvement. An assistant must also be available to help with launching the application in the operating room and handle possible challenges with spatial model positioning.

In the specific domain of breast surgery, Perkins *et al.* [12] suggested a marker-based AR application for lumpectomy, a surgical procedure to remove cancer or other abnormal tissue from the breast. The developed system uses the Microsoft HoloLens to allow the surgeon to view a tumour on the patient's real breast based on pre-operative imaging. The system works by putting six MR-visible fiducial markers around the surgery site during the magnetic resonance imaging (MRI) process, and then putting AR markers at the same position of those during the surgery. These markers are then used to register the patient's breast with the MRI during the surgical intervention (see Fig 6), allowing the tumors that were visible in the MR images to be

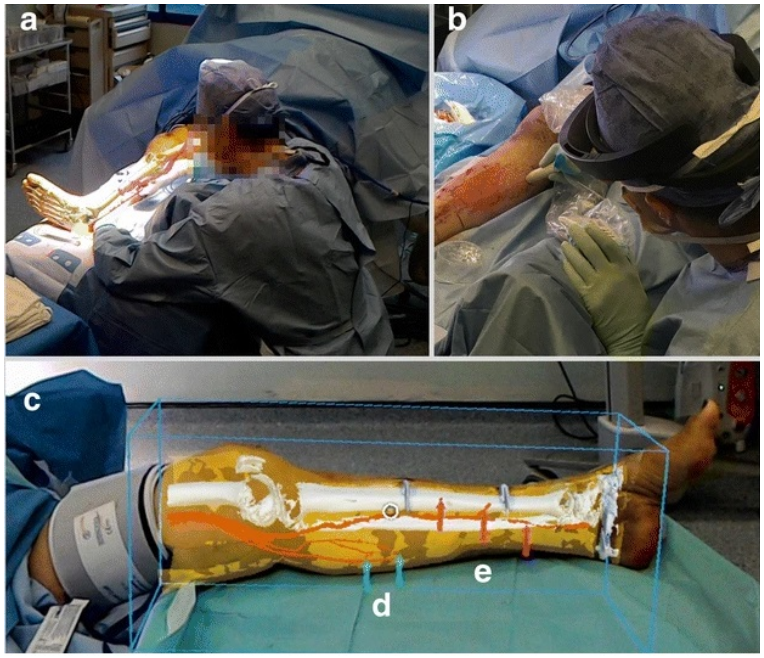

Figure 5: A developed AR system for flap surgery [10]. (a) the surgeon in the operating room; (b) confirmation of perforator location with audible Doppler ultrasonography. (c) overlay of the 3D model on patient's leg, as well as a bounding box locating the leg.

projected at the correct position on the patient's body. Although the system could compete with the traditional method, i.e. palpation to determine the location of the tumour, the authors write that it was prone to error as the position of the patient's arms can affect and deform the breast. This introduces error in the registration, and thus the location of the virtual tumour may be misaligned from the real tumour.

Rahman *et al.* [13] created a mobile augmented reality application to visualize breast tumours for a biopsy procedure, based on pre-operative MRI or CT images. Their application allows the surgeon to have "X-ray vision" by looking to the surgery site through the smartphone and seeing a tumour's size and position projected onto the patient. The 3D virtual tumour model is segmented from MRI or CT images. For AR visualization, the Vuforia [14] Object Tracking tool is used to detect where the 3D model should be projected. By using this feature, the authors were able to project the 3D models of the breast and the tumors on a breast phantom in real time. They performed an experiment in order to compare their framework with the traditional way of targeting biopsy needles in the same phantom breast. The mobile device that was used for testing was an android phone (Samsung Note 5) with 800x600 pixel

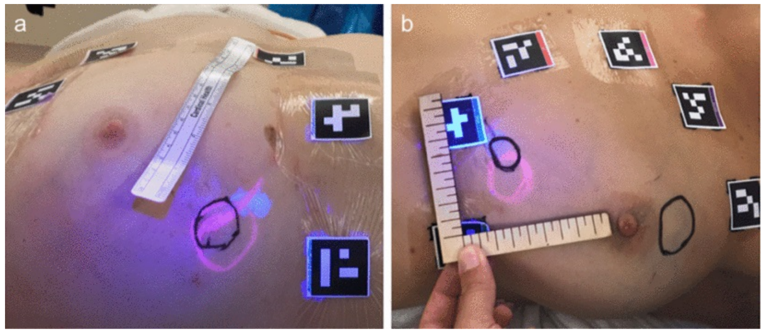

Figure 6: Augmented reality overlay of breat tumour markings in two patients [12]. The pink marks are made using only the images taken before surgery, the blue marks are made with the aid of HoloLens, and the black marks are made by palpation. (a) Due to the change of arms position between the MRI and surgical position, in this patient the HoloLens marking is partially displaced. (b) In this patient, the surgeon who was relying on palpation to locate the tumor, initially marked a lesion that was far off from the surgery site (the black mark above the nipple). After receiving additional information about the approximate position of the tumor using the MRI images, a new mark was made which was closer to the marks made by the other two methods (the second black mark on the lower part of the breast). The initial confusion could have been caused by a benign tumor that was not visible in the images and was not part of the surgery.

resolution. Due to errors on the 3D object tracker side, the system was prone to inaccuracy although no error metrics were reported in the paper.

2.1.2 Augmented Reality for Breast Reconstruction Surgery

Although AR is becoming more popular for surgery planning and interventions, there has been little research aimed specifically for breast reconstruction surgery. The one work that we are aware of and is most similar to ours comes from Norberg and Rask [15] who developed a Microsoft HoloLens AR application that allowed users to project a predefined breast model on the patient's body. The application scans the patient's body using the HoloLens' infrared sensors, and creates a 3D mesh of the patient's torso that is then smoothed using a Laplacian filter. The torso model is used as a base for the AR breast object to be placed on. An RGB image of the scene is also taken during scanning using the HoloLens's web camera and used to detect the texture of patient's shirt. This texture is applied on the hologram and make it more realistic (see Fig 7). The user can interact with the hologram by rotating, scaling

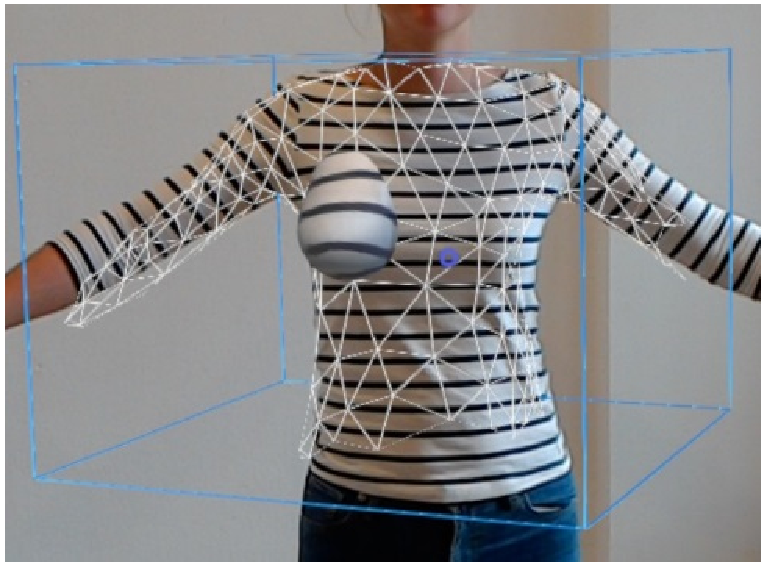

Figure 7: Position and texture of the breast model in Norberg and Rask HoloLens application [15]. The texture is copied from the subject's torso and applied on the breast model, in order to make it blend in with the torso and look more realistic.

and moving it in order to get to their desired shape, size and position. However, since their 3D model is predefined, the options are limited and there is no way to see the deformation of the model in different positions. The developed application was a proof of concept and no user study was done. This is the only research work we are aware of that focuses on augmented reality for mastectomy planning.

2.1.3 Commercial Applications in Plastic Surgery

There are many commercial applications for cosmetic and plastic surgery. These applications mainly allow the surgeon to modify images of the patient and show them an estimation of the final look after the surgery. Some of these applications, such as Mentor's New You Visualizer [16] and Kaeria EURLP's Plastic Surgery Simulator [17], can be used for breast augmentation surgery where both breasts are modified at once (Figure 8). Other more complicated applications such as Crisalix [18], scan the patient's body and create a 3D model of their torso to be used as their reference, and allow the surgeon to modify the model based on their preference (Figure 9). Since the final look is presented as a 3D model, the user has a more realistic understanding of the results. These commercial applications create the output as either an image or a 3D model as an external object rather than showing the changes on the patient's

Figure 8: An example simulation using Mentor's New You Visualizer [16]. The user interface provides options for changing the size, angle, shape and volume of the added breast shape, as well as adding a bra. There is no option for profile view, and the color and texture of the added shape can only be chosen from a limited set of skin colors, which can not match the image skin tone or clothing perfectly.

body itself. An exception to this is the Illusio [19] software, which addresses this issue by using marker based augmented reality. The patient has to wear a patterned piece of fabric around their breast area, so when the surgeon looks at her body through a tablet camera, the application can detect the pattern and substitute it with 3D models of different breast shapes in the process of rendering the video. These models can be modified in different aspects such as shape, size and angle, either on each side independently or on both sides simultaneously.

The most important difference between breast reconstruction and breast augmentation is in cases where only one breast has been removed during mastectomy and needs to be reconstructed. In this case, the surgeon has to try and recreate the shape of the natural breast on the contralateral side of the patients body. So not only is it useful to be able to have a visual estimation of what the final result will look like, it is also important to be able to compare that result to the natural side of the patient's body for the sake of symmetry. Our aim in this dissertation is to compare available implants to the patient's healthy breast, and suggest the implant that will provide the most symmetric results following a single mastectomy.

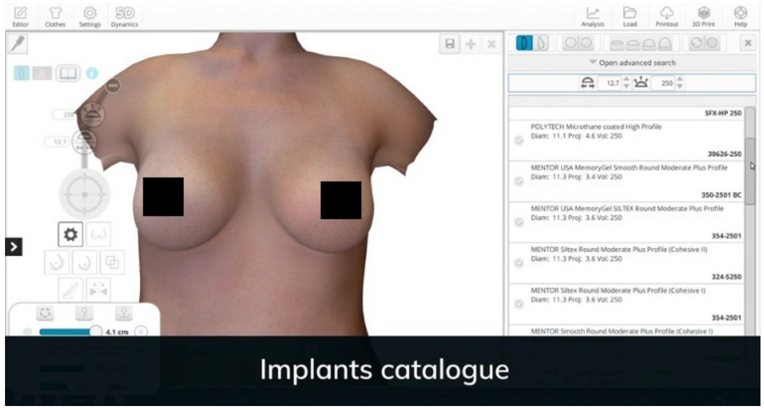

Figure 9: A demo provided by Crisalix website [18] which demonstrates a 3D model that is created by scanning a subject's body. The surgeon has access to a catalog of a variety of implants, and can test each one of them on this model to see the approximate final results.

2.2 Finite Element Method

The Finite Element Method (FEM) is a numerical method for finding a solution to a complicated mathematical problem by dividing and replacing it with smaller, simpler problems. In other words, when there is no sufficient analytical tool to solve the problem as a whole, it can be broken down it into smaller problems (called elements) that can be individually solved with the tools at hand. This allows for an approximate solution to the larger problem at hand.

The FEM has been used to solve problems of solid and structural analysis, thermal analysis, and fluid flow analysis, to name a few. It can be used to solve physical problems in an engineering system, such as the mechanics of different structures, or understanding the physical behavior of a complex object. Here, we focus on bio-mechanical modelling which has been used to consider for example how different anatomical structures, e.g. a liver or breast, deform under forces such as those applied from surgical tools or even gravity.

As mentioned above, in the FEM, the problem of interest is divided into smaller parts, which are called elements. The interconnection points between these elements are termed nodes or a nodal points. The quantity that we are trying to compute (in our case, deformation and displacement of different parts of the 3D model) is called the field variable, as its value inside each finite element can be estimated by a simple function [20]. When considering FEM for bio-mechanical modelling, the main steps are as follows:

1. Modeling the geometry, simplifying and approximating where necessary, in a way that in can be then discretized by elements. These elements will be interconnected at two or more common nodes. The number of elements is decided by the level of accuracy that is needed, and the computational resources at hand. The optimum number of elements is typically unable to cover all of the details of the main geometry.

2. Discretizing the geometry into finite elements, also called meshing. The elements are usually tetrahedral, triangular prisms, or rectangular bricks for a 3D domain. Triangular elements are the most flexible way to discretize an object.

3. Defining the properties of the materials used in each element, so that different physics can be simulated. These properties are either available in commercial material databases, or should be calculated based on experiments or smaller simulations.

4. Applying boundary and loading conditions. Boundary conditions are the value of the field variables on the boundaries of the field. Physical constraints also need to be defined.

5. Assembling the element equations in order to find the global equation system for the entire problem. In other words, equations assigned to each element are combined, using element connectivity. The desired equation should be formulated as:

   $$[K]\vec{\Phi} = \vec{P} \tag{1}$$

   where [k] is the matrix of assembled stiffness, $\vec{\Phi}$ is the vector of nodal displacement, and $\vec{P}$ is the vector of nodal forces for the complete structure.

6. Solving the global equation system for unknown nodal displacement. The nodal values will be produced as a result of this step; and lastly,

7. Computing additional results, such as strain and stresses.

2.2.1 The Finite Element Method in Surgical Planning

Finite element analysis and modelling have been widely used in surgical planning, and breast surgery is no exception. Han *et al.* [21] proposed a hybrid FEM framework for registering prone to supine MR breast images. Their aim was to register preoperative prone images to intraoperative supine images of the patient in order to increase the accuracy of determining the size and location of the tumours in the operating room (OR). Their framework combines biomechanical models with non-rigid intensity-based image registration methods in order to recover deformations caused by gravity and the change in the patient's body position.

The framework consists of seven steps as shown in Figure 10. First, the prone breast MR is segmented and a finite element model is created based on the segmentation. The material parameters and breast position are initialized, so that in the third step, the effect of gravity on the model and the resulting deformation can be calculated using an FEM solver. Next, the displacement of each voxel within the breast in the prone position is calculated, by using finite element shape functions. By adding the displacement of each voxel to its new position on the original MR image, the supine MR image is computed. The resulting model is then aligned to the real supine MR image using a block-matching rigid transformation, so that the similarity between the two can be measured. The process iterates until the similarity is maximized. The resulting supine image is then registered to the original supine MR image using affine and non-rigid intensity-based image registration methods.

For the sake of simplicity, the authors considered the breast to be made of one type of material, which can be described by the neo-Hookean hyperelastic model. A neo-Hookean model (material) is any material that obeys a natural generalization of Hooke's law, meaning it has a deformable elastic texture that is not compressible. [22] In order to measure image similarity, normalized mutual information was used, defined as

$$\mathrm{NMI}(A, B) = \frac{H(A) + H(B)}{H(A, B)} \tag{2}$$

Where $H(A)$ is the Shannon entropy of the original supine MR image, $H(B)$ is the entropy of the result of the finite element prediction, and $H(A, B)$ is the entropy of the joint distribution of the original supine MRI and the FE predicted MR image for supine position.

In order to evaluate the performance of their framework, the authors compared

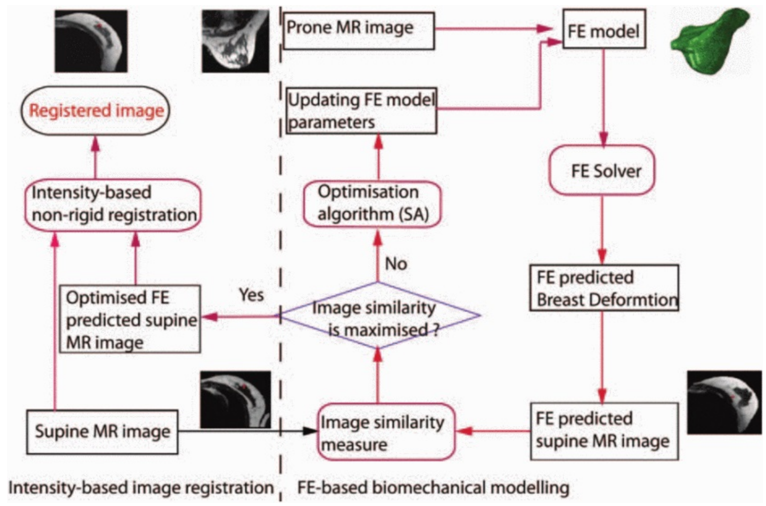

Figure 10: The workflow of the framework proposed by Han *et al.* [21]

their results with two different registration methods: affine registration followed by non-rigid B-spline based free form deformation registration and biomechanical model based registration. In this method, the object of interest is enclosed inside a B-spline object, and the deformation of the latter is computed in order to achieve the deformation of the former. This allows for a more computationally efficient calculation. Visual measurements revealed that neither of these methods were able to accurately register the images, while the hybrid method achieved the best results. The authors used eight MR-visible fiduciary markers as ground truth, which were positioned on the breast surface during the imaging process to calculate registration error. The registration methods failed in showing a good alignment, so only the error from the hybrid method was calculated. The root mean square error of all eight nodes was 2.8mm and the maximum error was 3.7mm. Figure 11 shows the results of each method, as well as the accrual supine MRI image as the ground truth.

In a similar work, Song *et al.* [23] developed a method to predict the location of tumors in the supine position, based on MRI images taken in the prone position. In their method, a 3D model is generated from the prone position MRI images, then by applying inverse gravity to this model a reference state is created, which is considered to be the shape of the breast with no external force applied to it. By adding negative gravity to the reference model once more, the deformation resulting in the supine position is calculated.

The 3D model of the breast is created by using a 3D thresholding and 3D region

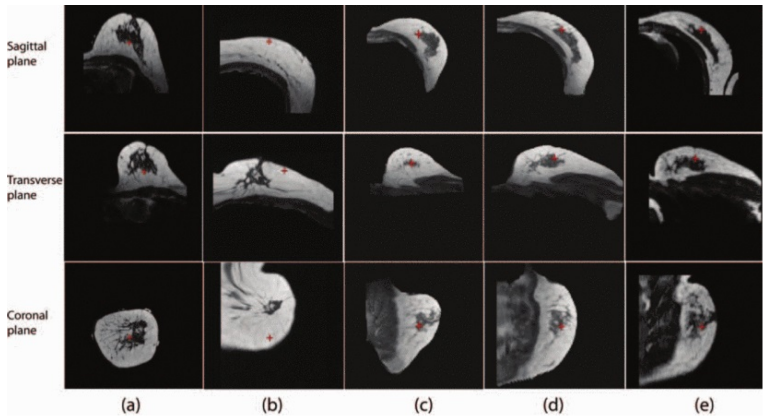

Figure 11: Results from Han *et al.* [21]. (a) Original prone MR image before registration. (b) Supine MR image registered using affine registration followed by non-rigid B-spline based FFD registration. (c) FE computed supine MR image using biomechanical model based registration. (d) Supine MR image registered using the hybrid method, and (e) original supine MR image.

growing method using the Mimics software [24] based on processed prone MRI images. The deformation of this model is calculated using the Mooney-Rivlin method (an extension of the neo-Hookean model, which can create more accurate results), using the finite element software Abaqus [25]. The authors evaluated their system by comparing the position of the tumor in relation to the nipple in their supine model versus its position based on ultrasound imaging. Specifically, the position of the tumor border was used for comparison. In three patient cases, the average Euclidean distance between the real position of the tumor and the prediction of their model was 4.31mm.

Azar *et al.* [26] proposed using the FEM to calculate the location and extent of a tumor in the compressed patient breast using MRI images taken before a biopsy procedure. The aim of this work was to ensure the needle would be accurately inserted into the tumour. In the biopsy procedure, the patient is asked to lie in prone position with the breast compressed between medial and lateral plates, and the location of the tumor is calculated based on contrast-enhanced MR images taken in this position. However, the pressure caused by these plates, combined with the deformable nature of the breast tissue, might change the enhancement characteristics of the tumour, thus making the tracking process very difficult. Moreover, localizing the tumour is done with static MR images, since it is not possible to do live imaging. To address this problem, the authors took the pre-operative images (without compression) and applied the same forces to the finite element model virtually to calculate the new location of the tumour.

Prior to creating the 3D model out of axial MR breast images, the images were manually segmented into parenchyma, fat and lesion tissue. These segments are used to assign different materials to different parts of the model, in order to make the simulation more realistic. An algorithm was used to calculate what percentage of each tissue type within the element by counting the number of voxels in each segment and assigning the material property that has the highest percentage of voxels in that segment. The model is created using BreastView software [27] and the deformation of the breast is computed by dividing it into a number of smaller displacement steps, using small strain theory. Strain was calculated using Cauchy's infinitesimal strain tensor formula:

$$\varepsilon_{xx} = \frac{\partial u}{\partial x}, \quad \varepsilon_{yy} = \frac{\partial v}{\partial y}, \quad \varepsilon_{=} = \frac{\partial w}{\partial z} \tag{3}$$

$$\varepsilon_{xyyz} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right), \quad \varepsilon_{x,z} = \frac{1}{2}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right), \quad \varepsilon_{yx,y} = \frac{1}{2}\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right) \tag{4}$$

Where displacement fields in x, y and z directions are defined by $u = u(x, y, z)$, $v = (x, y, z)$ and $w = (x, y, z)$.

The author's proposed method was tested on one patient with a small cyst in their left breast, which was used as an inner landmark for tracking displacements inside the organ. Two vitamin E pills, one towards the superior part and another towards the inferior part, were taped to the surface of the breast as exterior landmarks as these appear as bright spots on the MR images. The deformation was evaluated in two different ways of compression: first, one plate was assumed to be immobile, and the full deformation was applied using only the other plate. Second, both plates equally pressed the breast, each plate responsible for half of the full amount. The results showed an imaging error of $0.9mm$ in the x and y direction, which are parallel to the plane of the image slices, and $1.8mm$ in the z direction. The one-plate compression showed more promising results than two plate compression in the deformation model, creating less errors in displacement.

As can be seen from the above described works, finite element modelling is a promising technique for calculating the deformation of soft tissue such as breast under various forces. Our goal is to use this technique to simulate the deformation of breast from prone to standing position on a 3D model created from pre-operative MR images. We aslo simulate the deformation of the available implants, from supine to prone position. By doing so, we can compare these two shapes to each other and find an implant that can recreate the shape of the patient's natural breast in standing position. This work is described in Chapter 4.

Chapter 3

Augmented Reality for Mastectomy Planning

A version of this chapter was presented at the MIAR (Medical Imaging in Augmented Reality) and AE-CAI (Augmented Environments in Computer Assisted Interventions) 2019 joint workshop at the Medical Image Computing and Computer Assisted Interventions (MICCAI) [1] Conference and was published in a special issue of the journal *Healthcare Technology Letters*:

- **Amini S**, Kersten-Oertel M. Augmented reality mastectomy surgical planning prototype using the HoloLens.*Healthcare Technology Letters: Special Issue: Papers from the 13th Workshop on Augmented Environments for Computer Assisted Interventions.* 2019 Nov 26; 6(6):261-5.

3.1 Introduction

According to World Health Organization, breast cancer is the most common cancer in women. It is estimated that over 627,000 women died from breast cancer in 2018 alone [2]. Treatment of breast cancer depends on the stage and type of cancerous tissue and includes chemotherapy treatment, surgery, and/or radiation. One common surgery that is used both to reduce the chance of developing cancer in the future and to remove cancerous tissue is prophylactic mastectomy. In this type of surgery, one

[1] The paper [28] received a best paper award at the MIAR & AE-CAI 2019 Workshop.

or both breasts are removed completely in order to reduce the risk of cancer re-occurrence or developing breast cancer. Bilateral prophylactic mastectomy (total removal of both breasts) has been shown to reduce the risk of breast cancer for at least 87% for women who have the hereditary breast cancer gene mutation (BRCA1 or BRCA 2) but have yet to be diagnosed with breast cancer, and for 97% for those with a previous diagnosis of the disease [29].

Studies have shown, however, that mastectomy has a negative impact on body image and on the quality of life of women [30]. One way to compensate for the body change caused by mastectomy is to do reconstruction surgery. In breast reconstructive surgery, a prosthesis is used to regain the lost shape and volume of the removed breast(s). The implants, which are usually filled with liquid such as saline or silicone, have a predefined shape and size, and it is up to the surgeon and patient to judge and decide which shape and size is best.

One of the main concerns of patients undergoing reconstructive surgery, is the look of the final result. This is especially the case when patients have only one breast removed (single mastectomy); making the modified breast symmetric to the natural one is very important to the patient but can be quite challenging for the surgeon. Dissatisfaction with the result of the surgery can lead to additional surgeries, where the surgeon will try to modify the size and shape of the breast to increase the patient's satisfaction.

The decision about the shape and size of the implant, is made by visually comparing available implants with the patient's breast. Currently, there are no tools involved to quantify the accuracy of this choice, and the surgeon has to rely on their experience and ability to predict the final result. As the implant is filled with liquid, it behaves differently when held horizontally or vertically. The shape also changes when the implant is surgically placed inside the patient's body, and the surrounding tissue applies pressure on it. Consequently, the current method that relies on the surgeon's knowledge and experience is prone to human error and not always accurate. Moreover, as the patient does not have the experience of the surgeon, they cannot engage in the process of decision making, as they are unable to imagine the final shape.

In order to compare different shapes, the surgeon has to order a small number of implants for each patient, which are known as "sizers". These implants are then used intraoperatively in the process of decision making, and their only purpose is to give the surgeon visual cues and make it easier for them to choose the right one. After the best match is chosen out of them, the rest are thrown away. As most implants are made out of silicone, they are not biodegradable, and thus the use of sizers can be considered an environmental issue, too.

To mitigate these shortcomings, we present a novel augmented reality (AR) application using the Microsoft HoloLens [11] head-mounted display unit. The application enables surgeons to visualize the final outcome of an implant, without relying on physical implants. In augmented reality, the real world (e.g. a patient in real life) is merged with virtual elements (e.g. virtual breast implants). In our case, we have developed software that allows the surgeon to examine a variety of available breast implant deformations in situ on the patient using augmented reality. By using a marker that is attached to the patient's chest, the final shape can be seen exactly where the implant would be placed, and can easily be compared to the patient's natural breast. This method of visualization aims to provide the surgeon with improved decision making and surgical planning regarding the implant, thus eliminating the need for sizer implants. It also allows patients to be involved in the process of decision making, as they can have an immersive experience of the final look and provide their opinion. Thus, the main contributions of this paper are (1) the development of a first prototype augmented reality system using the Microsoft HoloLens for mastectomy planning, (2) the evaluation of the ability of users to recognize slight differences in shape of different implant holograms and match them to a physical shape, and (3) a usability evaluation of the prototype.

3.2 Related Work

There has been little research aimed at developing AR applications for surgical planning of breast reconstruction surgery. One recent work was proposed by Norberg and Rask [15]. In their work, the Microsoft HoloLens enables users to place a predefined breast shape on a patient's torso and applies a texture similar to a patient's clothing on top of it. This is accomplished by first scanning the patient's body using the HoloLens infrared sensors and smoothing the resulting mesh using a Laplacian filter. The mesh is then used as a base for the breast hologram to appear on. In order to make the hologram more realistic, the texture of patient's shirt is applied to the hologram and saved using the HoloLens web camera. The user can rotate, scale and move the breast hologram to get the desired shape, size, and position. Contrary to our software, their system does not provide shapes acquired by using real implants and is limited to a predefined 3D model, hence the purpose is not to provide computer-assisted decision making in terms of the implant size. This is the only research work we are aware of that focuses on using AR for mastectomy planning.

There are many commercial apps for cosmetic surgery, which let the surgeon modify images of the patient, in order to show them how their body will look like after the surgery. Some of these applications are capable of being used for breast augmentation surgery, such as Mentor's New You Visualizer [16] and Kaeria EURLP's Plastic Surgery Simulator [17]. More complex applications such as Crisalix [18] use a 3D scanned model of a patient's body as their reference and alter the model based on the surgeon's preference. As the results are visualised in 3D, the user has a more realistic understanding of the final look. However, all of the above-mentioned applications show the changes in a model or image, so the user sees the results as an external object and will not see herself in her new body. Illusio [19] has addressed this issue by using marker-based AR. For using their app, the surgeon will wrap the area of interest with a patterned piece of clothing, and then view the patient's body through a tablet camera. The app then substitutes the pattern with the 3D modelled breasts in the process of rendering the video. The surgeon can alter this model in shape, size, and angle, either on each side of both sides. The main difference between the use of software for breast augmentation and breast reconstruction is that the latter must also consider the shape of the natural breast. When only one breast is going to be reconstructed, there is not much that can be done to change the size and shape of the natural breast. Hence, the most important aim of our software is to compare available implants with the patient's breast and suggest the one that is the most symmetric with the breast that is going to be preserved.

AR has also been used in other surgeries preoperatively. Fushima and Kobayashi [9] suggested a mixed reality system to be used in maxillofacial surgery. They use the results of 3D-computed tomography to reconstruct the 3D shape of the patient's skull and jaw bones. This model is synchronised with a dental cast using three titanium spheres as reference points. Pre-operative planning is done by transforming

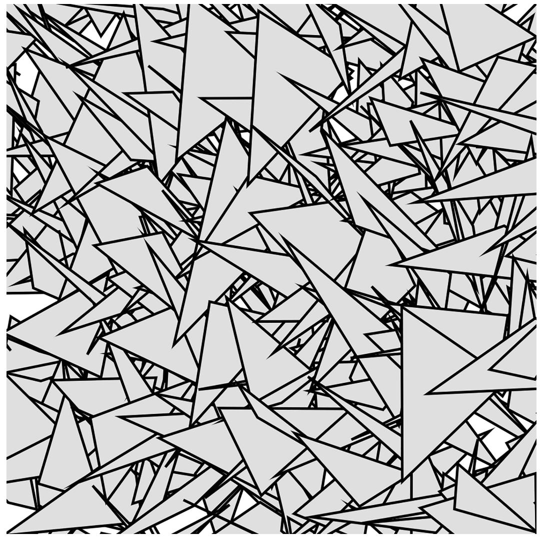

Figure 12: Pattern used as marker for our AR application which uses Vuforia. An ideal marker for use with Vuforia has to be rich in details, have good contrast, and not include any repeating pattern. This texture was generated by covering a plain surface with random triangle outlines.

and moving the 3D cast model. In comparison with the work above, our work does not rely on any medical images, and thus requires different solutions.

3.3 System Description

Our system comprises a HoloLens device running in development mode, a custom developed AR application, and a predefined pattern used as the marker for AR (see Fig. 12). The application was built using Unity version 2018.1.0 and uses the Vuforia SDK [14] to handle the AR functionality. Vuforia allows developers to define patterns as markers that can then be used for marker-based augmented reality. A database of these patterns is then created and the markers can then be downloaded and added to a given application. An ideal marker for use with Vuforia has to be rich in details, have good contrast, and should not include any repeating pattern. In order to satisfy these conditions, a texture was generated by covering a plain surface with random triangle outlines (Fig. 12).

Vuforia also has a feature called extended tracking, which saves the position of the marker in the world; using this feature, even if the marker is lost from the user's point of view, the augmented object will keep its last known position. The developed

Figure 13: Air tap hand gesture [11] used for selecting the menu items in our application.

application runs on the HoloLens device, which both serves as the camera and handles user inputs (hand gestures and gaze movement). The user can interact with the application using a holographic user interface (UI). The UI consists of a pointer that can be moved by head rotation, and 3 holographic buttons that can be selected by gazing at them and triggered by doing a hand gesture. We used air tap as trigger, which is one of the default gestures that HoloLens is capable of recognizing, and is performed by the user holding their hand upright, raising their index finger (ready state) pressing their finger down (tap) and back up (release state), as can be seen in 13. The UI follows the user's head rotation and position, and it is always visible in the field of view of the user. The buttons allow the user to choose between seven different implant shapes (described below), and to hide the menu.

It should be noted that voice recognition was also tested in an early version of the prototype, however, we chose the air tap as voice inputs were often not recognized by the system, particularly when users had an accent when speaking the English commands. The application starts with the HoloLens scanning the environment using its video camera, and looking for the marker we have defined in our Vuforia database. Since the implant model is set to appear on top of the marker, the position of the marker is quite important. The marker, which is 17.5 cm * 17.5 cm, must be attached to the patient's clothing or body, where the implant will be placed. When the marker is found, the implant hologram will be placed there. After the HoloLens detects the marker, the first available shape appears as a hologram in the middle of the marker by default, assuming that the marker is in the correct position. Using the extended tracking feature of Vuforia, we ensure the user can walk around the patient and look at the shape from different angles, without losing sight of the implant when the tracker

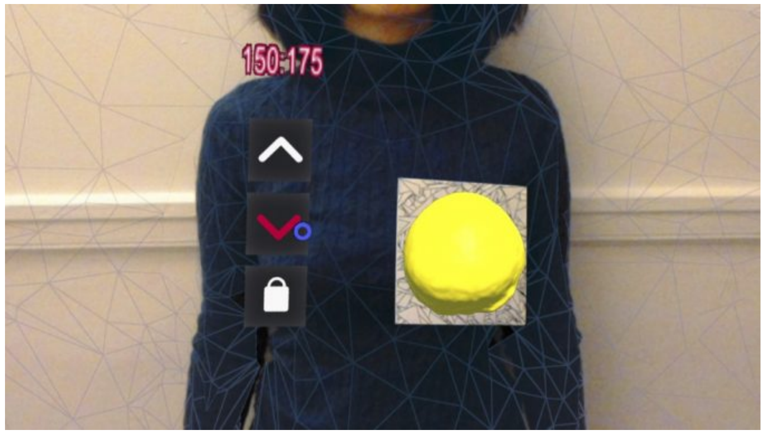

Figure 14: Screenshot of the HoloLens application during use. The marker is attached to patient's clothing, and the hologram of implant is placed on the center of the marker. The Holographic menu can be seen on left, as well as the cursor which is placed on 'down' button. The amount of saline needed to be injected in each chamber to gain this shape can also be seen on top of the menu, in milliliters.

is out of the point of view of the HoloLens. The user can also use the up and down buttons by gazing at them and performing an air tap, in order to navigate between available shapes and find the best match. Each button changes color when the user gazes at it, hence the user knows when the pointer is where they want to click (Fig. 14). Moreover, the cursor changes to a hand shape when the user's hand is detected in the field of view of the HoloLens in ready state, so they know when the device is enabled to react to their hand gesture.

The application features 6 different shapes based on a custom implant that we developed with two chambers. The two chambers, which can be filled with water using separate input tubes, enabled us to create a variety of different and more natural shapes. This implant was cast by pouring Dragon Skin silicone [31] type -35, in a 3D printed mold that was created using CATIA software [32]. The varying shapes were gained by injecting different volumes of water in each chamber (Table 1), and attaching the water-filled implant to a medical mannequin wearing a special stretch shirt. The shirt mimics the role of skin by adding pressure on the implant and deforming it (see Fig. 15).

After injecting the desired volume of water into each chamber, the K-Scan software [33], which allows for scanning objects in 3D by using a photogrammetry technique, was used to scan the resulting 3D shape. We used a Microsoft Xbox One Kinect

Shapes	Volume added to the upper chamber, ml	Volume added to the lower chamber, ml
A	150	235
B	150	175
C	210	175
D	210	140
E	245	200
F	245	150
G	105	105

Table 1: Volume of water injected in the custom implant for each shape

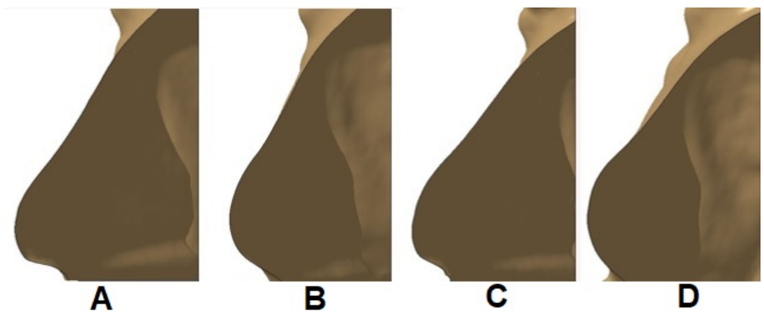

Figure 15: The application features 6 different shapes based on a custom implant that we developed with two chambers. Four of the custom shapes gained by using our developed implant shown on a medical mannequin are depicted here.

sensor [33], which has a depth camera, in order to take multiple scans from the implant from different angles. These scans, which consist of a dense point cloud of the scene, were inserted into K-Scan, aligned and merged together, and created a 3D model of the scene. We then cropped the implant shape out of this model and saved it as an .obj file. The application has access to these files in the memory and can summon them based on the user's input.

3.4 Experiment

We tested the usability of our software in a user study, where participants were asked to browse the 7 available implant shapes and compare them to a real implant. The implant used in this experiment was the same custom implant that was used to create the shapes mentioned in Table 1, and it was inflated with 110ml of water in the top chamber and 110ml in the lower chamber to create shape G with some slight change in the size. The real implant was placed on a flat surface and covered with an elastic covering, to mimic the environment that was created in the scanning process (see Fig. 16). The marker was also put on the same surface next to the implant, so the holographic implant will appear side by side to the real implant, which serves the role of patient's natural breast in this concept. The marker position was chosen based on users' personal preference. In addition to the cursor and the buttons giving feedback to the users' inputs, the 3D models were assigned with different colors, to let the user know when they have successfully triggered a button to observe the next model.

Our study sample was composed of thirteen subjects (aged 21-40 (median 26), 5 females and 8 males). They were all students, studying computer science, software engineering, electrical engineering or mechanical engineering. Eight of the participants had previous experience with the HoloLens or had seen how HoloLens works before. Nevertheless, all subjects were briefed on the concept of augmented reality and holograms, HoloLens functionality and the reason of the study. They also received a briefing on the system functionality, i.e. the HoloLens input system (hand gestures and gaze movements) and how to interact with the user interface. Before the beginning of the trials, the subjects were presented with the test environment, and were asked to interact with the user interface to summon different shapes on the marker. The goal of this pre-test session was to let subjects practice in order to reduce a potential learning bias.

The subjects were informed that there might be no exact match to the real implant, and they need to find the shape that looks the most similar. No time limit was set for the decision-making process, and the subjects were supervised by the researcher to guide them about the system when necessary. After the subjects completed the study, they were asked to fill out the System Usability Scale (SUS) [34] questionnaire, which is a standard usability questionnaire. SUS consists of ten five-point questions, and is a well-known test that is used to estimate the usability of a system. A system that scores 68 or above is considered usable and above average. The subjects were also asked to rank the system on a scale of 1 to 5, on how helpful it was in comparing shapes and finding the best match.

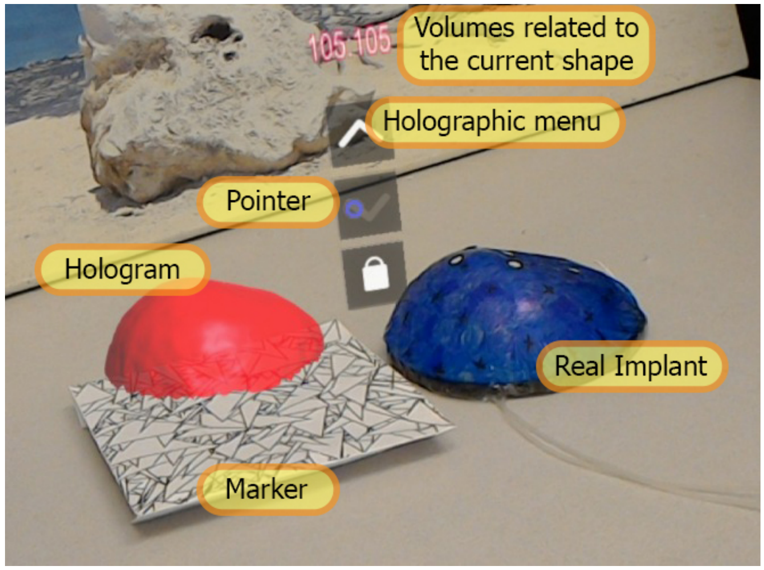

Figure 16: The experiment setup used in our study required subjects to match the holographic 3D shapes available in the application, with a real implant that was filled with 110mL of saline in each of its chambers. The implant is covered with elastic wrapping, to mimic the setup which was used for scanning shapes in Table 1.

3.5 Result

On average, it took the subjects 7 minutes and 28 seconds to choose the best matching shape and declare it. Each subject took from 2 minutes and 44 seconds to 20 minutes and 47, with a median of 6 minutes and 11 seconds. The time taken to see all the shapes and compare them to the real implant for the first time varied from 2 minutes and 21 seconds to 9 minutes and 48 seconds, with an average of 3 minutes and 43 seconds. As this time was close for all subjects, the variation between times that took each subject to make a decision seems to be related to subjects' personal sense of making sure of their final choice. In terms of subjects' choice of shape, as can be seen in Table 2, 7 subjects chose shape G as the best match which was considered to be the correct answer. Other shapes that were suggested by the subjects include shapes A, E, F, being chosen 3, 1 and 2 times respectively. There was no need to move the marker during the process of decision making, and the setting remained unchanged for each trial. In terms of qualitative evaluation, the SUS score given by the users varies from 97.5 to 50.5 (see Table 3), with a median of 70. The system was considered to be well integrated, with 57 positive points out of the possible 65 points. However, 10 out of 13 users found the system cumbersome to use, 8 believed that a

Shape	Times being chosen
G	7
A	3
E	1
F	2

Table 2: Shapes that were chosen as the best match

SUS Question / subject	S1*	S2*	S3*	S4*	S5*	S6*	S7	S8	S9*	S10	S11	S12*	S13	Sum
Question 1	4	3	2	5	5	2	4	3	2	3	3	4	2	42
Question 2	1	1	1	1	2	2	3	3	2	1	4	3	2	26
Question 3	5	5	5	3	4	4	5	3	4	2	2	3	3	48
Question 4	1	2	2	1	2	3	3	1	4	4	4	4	5	36
Question 5	5	5	5	5	5	5	3	4	5	3	5	4	3	57
Question 6	1	1	1	1	1	2	1	2	2	2	1	3	1	19
Question 7	5	2	4	3	5	5	4	4	4	5	4	4	5	54
Question 8	1	1	1	3	2	2	3	3	3	2	4	4	4	33
Question 9	5	5	5	4	3	4	4	3	4	4	5	3	3	52
Question 10	1	1	2	1	2	1	2	1	3	3	3	3	4	27
SUS Score	97.5	85	85	82.5	82.5	75	70	67.5	62.5	62.5	57.5	52.5	50	

Table 3: Usability assessment done using SUS. The subjects that are distinguished with a star sign had previous experience with HoloLens.

technical person must always be present to support the users in order for them to be able to use the system correctly, and 12 believed that the system is unnecessarily complex. The cumulative scores given for these topics were 33, 36 and 26 respectively.

Overall, the system gained an average of 71.5 on SUS scale, meaning that it passed in this evaluation by 3.5 points. Out of 13 subjects, 12 users found the software useful for comparing shapes and objects, giving it an average score of 4.23 out of 5.

3.6 Discussion

It can be deduced from Table 3 that the users' previous knowledge about the HoloLens affects their experience with this system. On average, the users who knew about or had tried HoloLens before, had an easier time learning how to interact with the user interface, and gave better scores to the system. These users are marked with a star next to their ID number in Table 3. However, both groups equally believe that the presence of someone as technical support would be necessary to have a successful experience with this application.

The main problem stated by the users was detecting the position of the cursor when the application starts. The HoloLens needed to be recalibrated for every single user, to make sure they can see the cursor, the menu and the holograms. Otherwise, the cursor could not be seen in the middle of the frame. This process takes 5 to 10 minutes, and makes the whole experience more time consuming and tiring. Furthermore, as the cursor is controlled by the user's head, it is not as accurate as users expect it to be. The cursor tends to move with every slight body movement and seems to be constantly shaking with users' breathing.

Another issue was caused by the limited field of view of HoloLens, which subjects needed to remember in order to let it detect the hand gestures. Although the cursor provides feedback when the user's hand is detected in ready state (Fig. 14) and turns into a hand shape, all subjects had to be reminded, constantly, to do the hand gestures in a way that the HoloLens can detect their hand movement. Moreover, being forced to stretch their arms in front of their body to fulfill this goal, was tiresome for the subjects and one of the main downfalls of the system. The subjects also found it difficult to get used to controlling the cursor by gaze movement, as they naturally do not turn their head to look at an object where they can see it just by moving their eyes over it. The users did not believe they would use an AR system in the long-term frequently. However, all users believed that most people can learn how to work with this system quickly, with this question gaining 54 points out of 65 possible points.

It is also important to note that all subjects had an engineering or computer science background, and none was plastic surgeon or had experience in a decision-making and mastectomy planning. Two aspects are important to note, first, it is possible that having an engineering background made it easier for them to understand technical terms and made their learning phase shorter. Second, all of the participants lacked the experience that plastic surgeons have from years of matching implants with human breasts. Hence, it can be hypothesized that once a surgeon passes the learning phase and learns how to interact with the HoloLens device, it would take them less time (in comparison to ordinary users) to choose the best matching shape out of the 3D models. In future work, we will study the impact of the system on plastic surgeons.

Another main distinction between our study and clinical practice is the number of available implants in real life, which makes the process of decision making more complex. For this study, as we did not have access to neither cosmetic implants nor a patient, a custom-made implant was used both for creating 3D models instead of a cosmetic implant, and for being compared against these shapes instead of patient's real breast.

Unlike Nornberg and Rask's work [15], the 3D models in our system are colored with plain colors and do not use the texture from patient's body. One main reason for this shortcoming is the presence of the marker, which is used to detect the breast area but on the other hand blocks visual access to patient's skin or shirt in that area. One possible solution is to access the skin tone or the shirt texture by taking a picture from the patient beforehand. However, for the sake of this study it was not an issue, as the implant itself was being compared to the 3D models. This will feature will be added in future work.

The current system relies on the use of a third-party platform for detecting the marker and placing the 3D model at the marker location. In the next steps of this work that will involve patients, we can eliminate the need for the marker and the third-party platform by automatically detecting patient's breasts by using visual features of their body.

We scored 71.5 for SUS, which makes our system slightly above the threshold to be considered usable. Since many of the issues that were raised involved interactions with HoloLens, it can be assumed that the score can be increased by using a simpler device. One possible approach would be to use mobile devices such as the iPad, which have a more tangible interaction interface and one which users are more familiar with.

3.7 Conclusion and future work

Our preliminary study showed that the idea of using augmented reality to find similarities in objects is considered useful by the users. Users were able to compare 3D models with a real object, without the need of having any of the reference objects present. Moreover, as all 3D models appear on the same spot on the marker, once the marker was on the right spot in relation to the implant, there was no need to set the position for each model, which saves time and makes the comparison less error prone by eliminating the effect of the change of implant position. However, the HoloLens was shown not to be the best platform to implement this system. All of the main problems stated by the users are related to the HoloLens and how to interact with it. Since the HoloLens behaves very differently from other devices that the users interact with on a daily basis, they have to go through a learning phase to be ready to use the system. Moreover, the way user input is received by the HoloLens, such as stretching an arm to do a hand gesture, was considered tiresome for the users and undesired. These obstacles make the system not an ideal option to be used on a long-term basis as all users stated. The system passed the SUS evaluation by 3.5 points, and it appears that resolving these issues could improve the usability of the system even more. Usability can further be improved by shifting to a platform that the users are more familiar with, such as mobile devices. Using devices that include a touch screen can help with cursor accuracy, eliminates calibration time, and is less tiresome for users to keep using for a long time. Moreover, in order for this system to be useful for surgeons, the database of the 3D models must feature shapes related to real implants that are currently used for reconstruction.

Although, this work was done on the basis of a need's analysis with plastic surgeons, our study did not involve domain experts. In the next part of this work we will work with domain experts to determine how the use of the system could help in decision making and reduction of the use of sizers during surgery.

As mentioned in Section 3.1, one of the main challenges for the surgeons is determining the deformation of an implant in different positions. We did not address this issue in this simplified implementation of the application, the current system can only show the shape of the implant in one position. However, if the system were able to predict the behavior of the implant in different positions, it would have a huge advantage over current methods. In the future we will look at FEM modeling to determine the deformation of the implant and natural breast in different positions.

Chapter 4

A 3D Modelling and Visualization Pipeline for Improved Decision-Making in Breast Reconstruction Surgery

In the previous chapter, we presented a prototype system to help surgeons determine the best implant in the context of mastectomy surgery by visualizing the 3D implant on the patient using augmented reality. One of the limitations of the system was that neither the implant nor the patient breast is modelled thus it is difficult to predict the behavior of the implant in different positions (e.g. prone versus supine). In this chapter, we explore the use of finite element modelling to find the best implant for a patient based on their pre-operative MRI images. The results of our preliminary study shows that FEM can be used to generate input for a comparison system, to rank the implants on their similarities to the patient model, and the decisions made by this system is similar to what human users would choose for each patient. A version of this Chapter will be submitted to the 2021 Augmented Environments in Computer Assisted Surgery Workshop at MICCAI.

4.1 MRI Breast Imaging

To create the 3D shape model of the breast, MR images, which are typically taken prior to surgery for diagnosis and treatment planning, are used. For MRI breast imaging, the patient lies in the prone position with their breasts placed through an opening in the imaging table 17. This method prevents the breasts from being compressed, allowing for better visualization. As a result, the only force applied on the breast is gravity, which makes it easier to calculate the deformation in the FEM step, as described in Section 4.2.4.

Figure 17: Patient positioning in MRI imaging process. [35]

4.2 Methods

The developed pipeline uses MR images from the Breast-MRI-NACT-Pilot dataset [36] available through the Cancer Imaging Archive [37] to create a 3D model of the patient's breast. The MR Images were acquired on a 1.5-T scanner (Signa, GE Healthcare, Milwaukee, WI) with an acquisition matrix 256 x 192 x 60, section thickness 2 mm; spatial resolution 0.7 x 0.94 x 2.0 mm^3 resolution. FEM is used to deform the model in order to recreate the shape of the breast in standing position while taking into account gravity's effect on the breast tissue. Finally, Hausdorff's distance is used

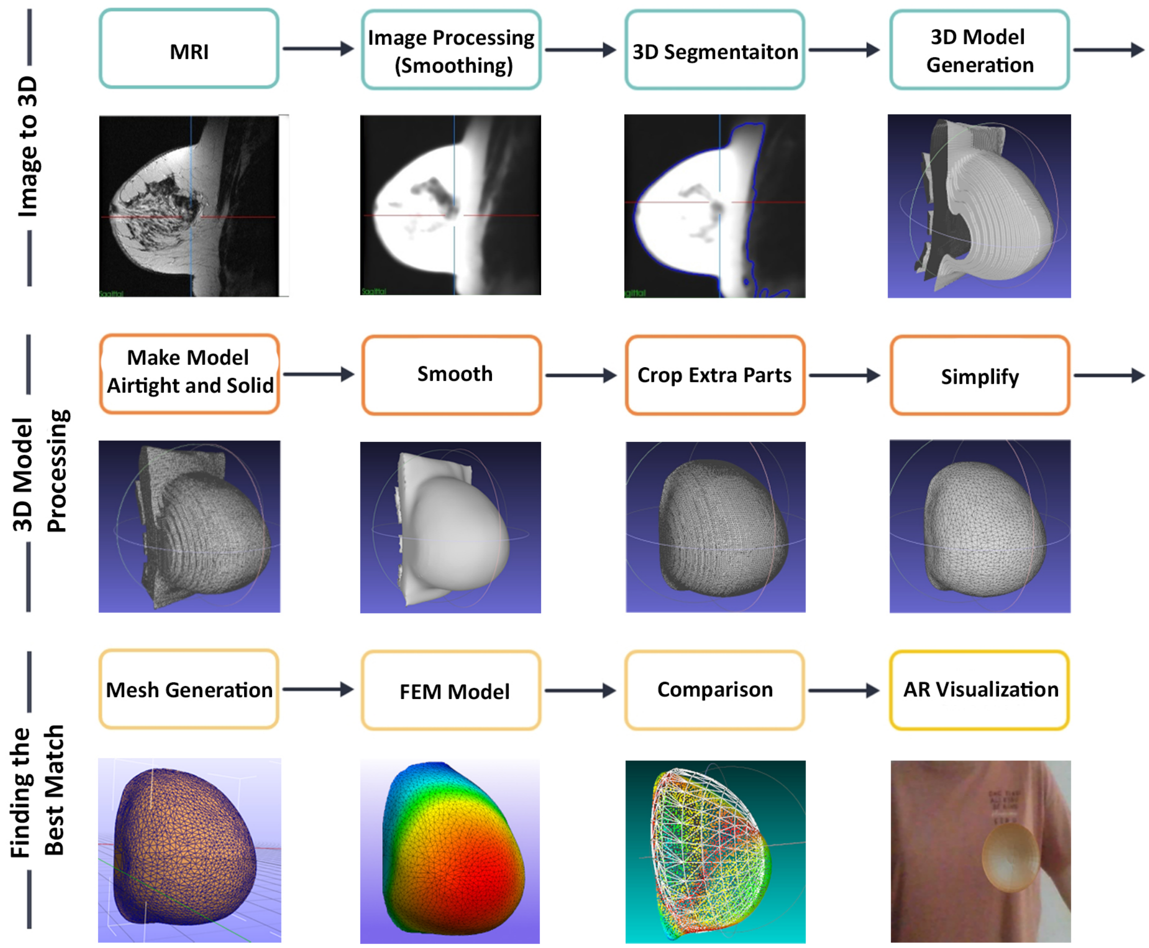

Figure 18: The workflow of our proposed system

to compare a patient's breast to a database of 3D models of sample implants, choosing the most similar candidates for the breast reconstruction procedure. The overall workflow of the pipeline can be seen in Figure 18.

4.2.1 Image pre-processing

For processing the MRI data, the Medical Imaging Interaction Toolkit (MITK) [38] software was used. MITK is an interactive interface to NifTK, an open-source software platform for processing medical images. The software was used for pre-processing the MRIs, segmentation, and 3D model creation.

The MRI images were first processed to remove noise and unnecessary details

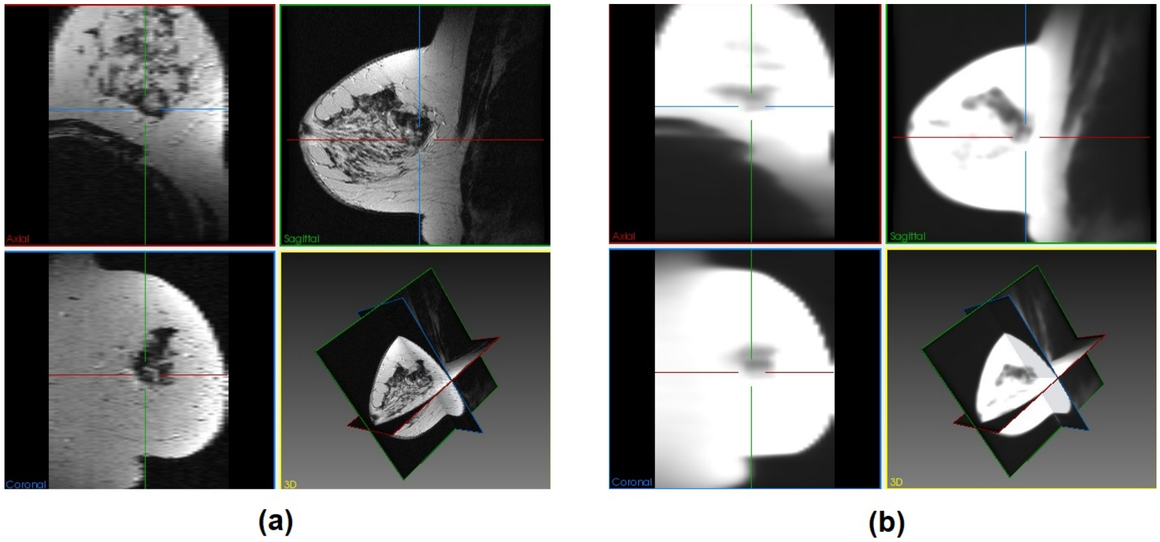

Figure 19: The result of the processing step, compared to the raw MRI image: (a) the original MRI and (b) the final result of the processing step after applying a Gaussian filter the original image.

such as veins and fatty tissue. To do this a median filter with a kernel of 5 was applied; the median filter retains edges while denoising the image. After applying the median filter, we noticed that the blurring has caused the areola to not be segmented correctly. To resolve this issue, a Gaussian filter with a variance of 2 was applied allowing for the edges to be softened and the areola to blend in with the nearest parts of the breast tissue without affecting the shape of the breast. The result of this process can be seen in Figure 19

4.2.2 Segmentation

In the next step, the MITK segmentation tool was used to extract the region of interest (ROI) using thresholding. Threshold values were chosen such that the curve of the breast shape was segmented as precisely as possible; values around 65 to maximum intensity (varying for each image). A hole filling function was then applied on the segmented area in order to get rid of any possible missed spots inside the area. Any extra chest tissue that was captured with thresholding was manually cropped from the 3D model. An example of the segmentation results can be seen in Figure 20

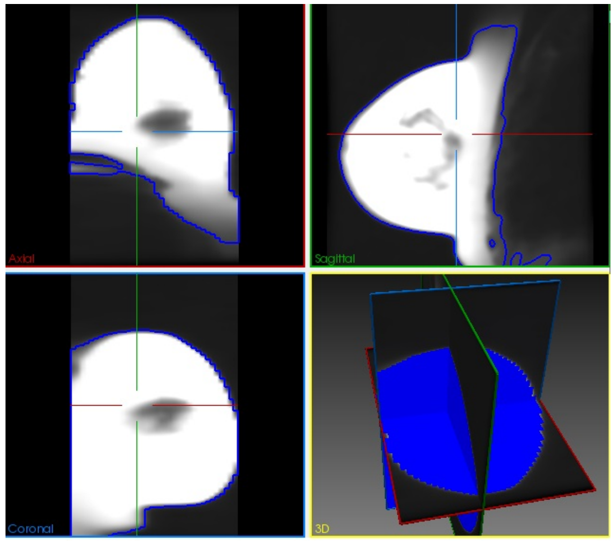

Figure 20: The result of segmentation using thresholding. We preferred to choose a wider range for the threshold in order to capture the curve of the breast shape completely, which led to also selecting some extra parts from the chest tissue. These parts were be manually removed from the 3D model.

4.2.3 3D Model Creation and Processing

The MITK Surface Extractor tool was used to create the initial 3D model of the patient's breast. As there are only 35 slices per MRI in our data set, the segmentation tool created rough edges in axial view (see Figure 20). In order to smooth the edges, a median filter with a radius of 3 was applied 5 times. The Surface Extractor tool uses the marching cubes algorithm [39] to create a 3D surface based on the segmentation done in the previous step. Figure 21 (a) shows the 3D model result of this process.

As seen in Figure 20 and Figure 21 (a) some tissue from the chest wall of the patient is segmented alongside the actual tissue of the breast. Therefore, the 3D model that is generated based on this segmentation contains some additional areas that need to be removed. The model also requires more smoothing to remove the rough edges. We used MeshLab [40] and MeshMixer [41] software for editing the 3D model. First, the model is made solid using MeshMixer's command "Make Solid", and most of the chest wall tissue, as well as any extra part that is not attached to the breast, is removed from it. This step is necessary to make sure the edges of the model have enough neighbour vertexes for the smoothing step. The final segmentation of the breast is done in MeshMixer after the model is processed in MeshLab.

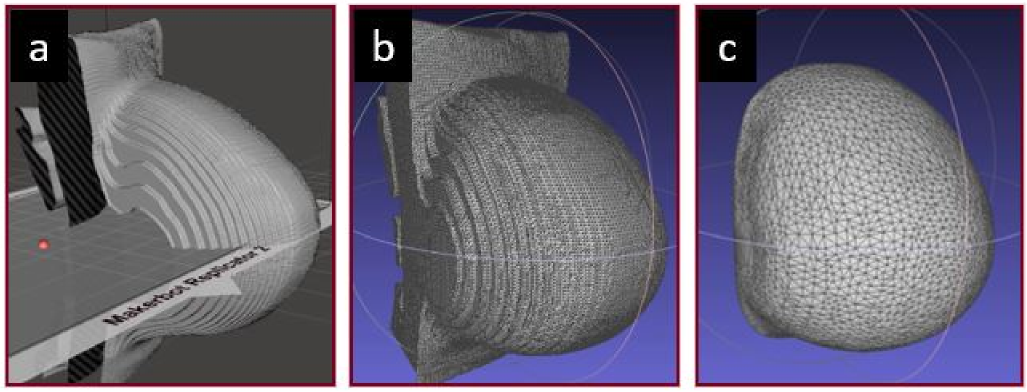

Figure 21: The processing steps of the 3D model generated based on the patient's MRI. (a) The result of using the MITK Surface Extractor tool. This model is a shell of the shape of the breast, and contains areas from the chest wall as well as rough edges that are removed in later pre-processing steps. (b) The patient model that is made solid, with any holes in the model being filled in. (c) The 3D patient breast model after processing in MeshLab and MeshMixer. The model is made smooth, areas outside of the ROI are removed, and the number of faces is reduced in order to make the next steps, especially FEM, more efficient.

Meshlab is used in order to smooth the model by applying a Laplacian filter (35 iterations). The Laplacian filter uses the average position of the adjacent vertices to each node, to calculate the new position for it. The model is then simplified using the "Quadric Edge Collapse Decimation" filter provided by MeshLab, in order to reduce the number of its faces from over 500,000 to around 5000. This allows us to create a mesh that is light enough to process efficiently, without losing too many details necessary in the comparison step. The model is then scaled in order to match the size of the implant models which were created based on Johnson and Johnson [42] implants.

4.2.4 Finite Element Modelling

FEBio Studio [43], an open-source finite element solver that is developed with a focus on bio-mechanical applications is used for processing. For the sake of simplicity, different tissue types of breast are all represented by one type of material, and the implant is also assumed to be made of a single type of material. The material used for modeling the breast tissue is based on the material properties used in Samani *et al.* [44]

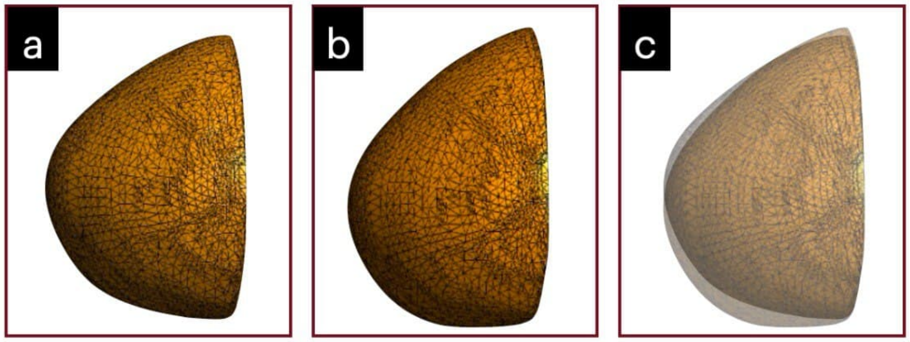

Figure 22: The result of FEM deformation of a model of a patient breast. Picture (a) shows the original model obtained from the MRI images of the patient. Picture (b) shows shows the deformed model after applying FEM on it. The comparison between the two can be seen in picture (c).

to define fat and fibroglandular tissue. They discuss that these two tissue types, which the breast is mostly made of, have virtually the same mechanical properties and can be described by a neo-Hookean material with the Poisson ratio of 0.495, and Young's module of around $3.24 \sim 0.61$ kPa.

The implant models used in our study are based on the size and shape of the most common implants provided by Johnson and Johnson Company [42]. The material used for modeling the implant is a neo-Hookean material based on Rynk*et al.* [45] work, who set the Poisson ratio for the silicone gel to 0.47, and the Young's module to 250 kPa.

The FEM process starts with creating a mesh out of the solid model using FEBio's TetGen mesh generator [46]. We use the Tet4 element type, which creates meshes with 4 node tetrahedral elements. For both the implant and the breast model, the smooth back side of the model is assumed to be fixed to the chest wall, hence a boundary condition is applied to this area. A force load of -10 in the z direction is applied to the model, in order to represent gravity in standing position. Since the breast MRIs are taken in prone position, a load of +10 in the y direction is also applied on the breast models, in order to cancel the effect of gravity in the lying position. The materials that were described before are applied on the whole model in both situations. The result of the deformation for a patient breast model can be seen in Figure 22.

4.2.5 Comparing the deformed breast model with implant models

Since each of the implant models is manufactured in a range of sizes for each specific shape, we chose one size of implant and use only models of that size for deformation and comparison. In other words, the best match of shape is found first, and the best size of the model to be used is determined by using the dimensions of the original patient breast model. Unlike the implants, where the posterior side is shaped like a perfect circle, the posterior side of the patient models is usually a semi-oval shape. Thus, the patient model is resized so that the long side of the chest is the same size as the diameter of the implants.

In the next step, the Hausdorff distance between the patient model and all implant models is calculated. The Hausdorff distance of two points sets is defined as the maximum distance of points in set 1 to the nearest point in set 2, defined as:

$$d_{\mathrm{H}}(X,Y) = \max\left\{\sup_{x\in X}\inf_{y\in Y} d(x,y), \sup_{y\in Y}\inf_{x\in X} d(x,y)\right\} \tag{5}$$

After calculating this distance for all of the implant models, the best matching implant in terms of shape is determined based on the root mean square (RMS) of all the distances. The implant with the smallest RMS is assumed to have the most similar shape to the patient's body. Based on this measurement, the top two choices on implant models are reported. The dimensions of the patient model is then measured in MeshLab to determine which size of those implant models works best in this case.

4.3 User Study

A user study was performed in order to assess the differences between user selected best implant and our developed method. A total of 8 implant models, as well as 6 patient models based on MRIs taken before surgery, were prepared for this study. Software to allow users to visualization navigate, see and interact with 3D models of the patients and the implants, compare them and choose the best match of shape for each patient model was developed and shared with a number of participants. The visualization software, which runs on a PC, shows the patient and implant models at hand as overlaying point clouds. In order to differentiate between the two, the

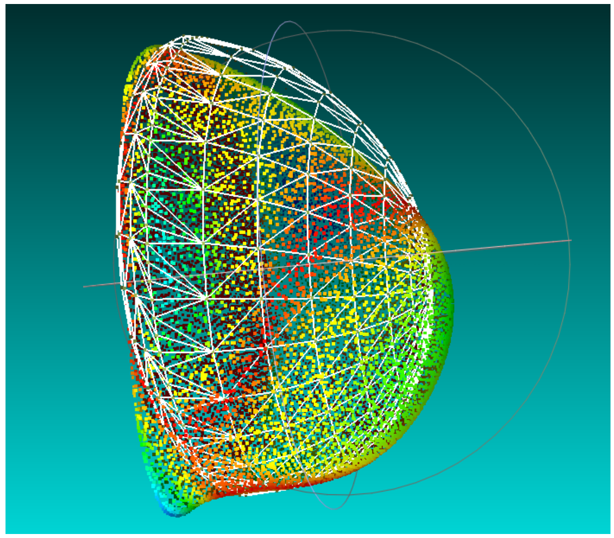

Figure 23: A patient breast model (depicted as a colored point cloud) overlaid with the best match of implant for it (depicted as a white wire frame model). The patient model is colorized in RBG format to show the distance in each point, with red being the closest distance and blue being the highest distance from the implant model.

implant points are colored in blue, and the patient points are colored in yellow. The user can navigate between implant models using the keyboard and interact with the model (rotation and movement). The flat back piece of the implant, as well as the flat part of the patient model (representing the part attached to the chest muscles) are placed on the same plane, and their center is on the same coordinates. After going through all the available implant options, the users were asked to choose one that they believe works best for that patient and report their choice. Due to current restrictions caused by the COVID-19 pandemic, we were unable to access surgeons in the testing phase of this project thus users were chosen from people who were familiar with medical imaging and 3D modelling.

A total of 7 raters participated in this study. The user chosen implants were compared to those chosen by the developed method (see Figure 25). As can be seen in the graph, in some cases there is no general agreement between users. This might be a result of the users considering different criteria when it comes to measuring the similarity between 3D objects. As a result of this situation, any case where more than 3 users have agreed on the same implant is considered a consensus. With this requirement, it can be seen that in the case of all of the patients except for number 5 (83.3%) , the users have agreed on at least one option.

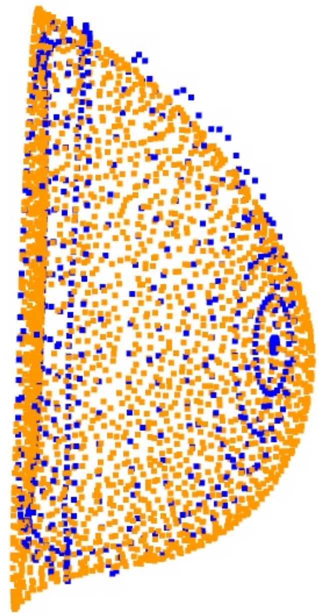

Figure 24: The visualization environment used for the user study. The patient model is depicted as a point cloud colored in orange, whereas the implant that the user is reviewing is shown as the overlaying blue point cloud. The flat face of the two models is on the same plane with the same coordinates to help the user to compare the two more effectively.

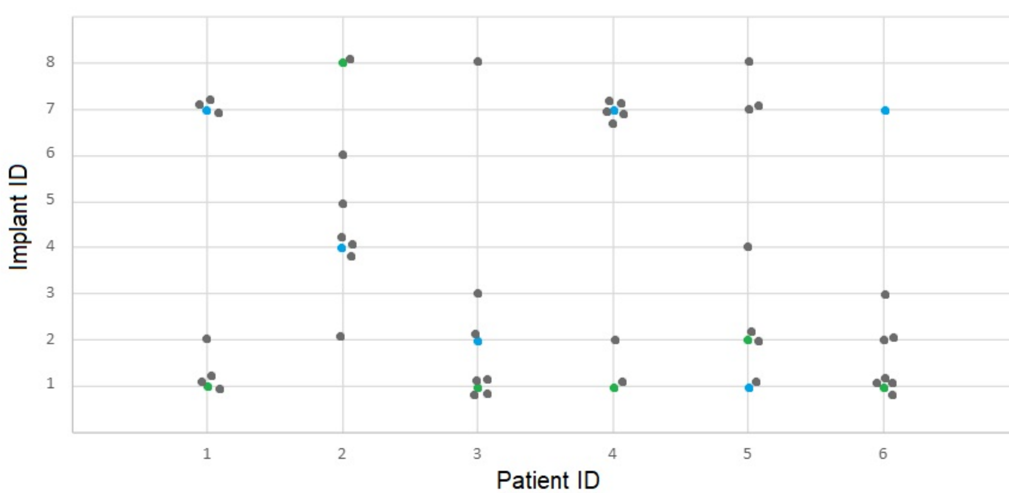

Figure 25: The users' answers for 8 implants and 6 patients, compared to the results achieved by our suggested method. The users' choices are depicted in grey. The green and blue points represent our method's first and second choice respectively. The implant IDs are assigned randomly.

4.4 Discussion and Conclusions

The results of the user study suggest that this method can make similar choices to human users, in a faster and more efficient way. As it can be seen in Figurechart-results, in all of the cases where more than 50% of the users have chosen the same implant for that patient, that option is either the first or the second choice of our method. The result of our method are not meant to be a gold standard but are aimed at suggesting to the surgeon the top implant options based specifically on the natural shape of a patient's breast. Thus, the aim of this system is two fold: (1) it allows for the surgeon to visualization the implant with the patient's natural breast (as imaged by MRI) accounting for gravity and (2) it may improve the decision-making process by reducing the number of implants that the surgeon has to go through by suggestion the best options from tens of implants to choose from.

As the system was developed as a proof-of-concept, it should be noted that only 8 implant models from a total of 22 possible silicone models of just the Johnson & Johnson implant catalogue were considered. A larger number of implants could have potentially also improved the rater agreement in the user study. It is also important to note that the user study was conducted in an environment affected by social distancing rules caused by the COVID-19 pandemic, which caused many restrictions. Our access to plastic surgeons and mastectomy patients were limited. In order to tackle this issue, a public database of breast MRI images was used for the creation of patient models, and the users where chosen from people who have the experience of working with medical images in their own area of expertise and not specifically breast imaging or reconstruction.

Finally, the MRI data that was used was obtained from a public access database of medical images, meaning we did not have access to the data on the actual implants that were used for those patients in the reconstruction surgery. We overcame this issue by developing a new, virtual visualization environment. It would be ideal to know the implant that was used for each patient, and compare it to the choice of our system. In the next step of this work, the system will be introduced to plastic surgeons for a more accurate user study, and the patient will be present for the comparison process. In addition, our AR application from Chapter 3 will be expanded to allow the surgeon to visualize the different implants as AR objects on the patient body, for better visualization (see Figure 26).

Figure 26: A mobile based AR prototype to visualize the choices of the system and let the surgeon see the final result on the patient's body.

Chapter 5

Conclusion

In this dissertation, we explored the use of augmented reality (AR) and finite element modelling (FEM) in surgery planning for breast reconstruction. We first investigated the use of AR in the process of choosing the right implant for the patient prior to the surgery, to see if AR can assist in the decision making steps of surgery planning. We developed a HoloLens application that allowed the user to go through a number of sample 3D models of different implant shapes and see them all on the patient's body as an AR object. Our results showed that AR can be useful in this context, making it easier to navigate between a number of implants. However, we also found that users would prefer a more familiar device, such as a tablet, instead of the HoloLens. Furthermore, this AR prototype had other limitations: the implant shapes were created by 3D scanning a custom designed implant and commercial implants were not provided. Furthermore, as a side effect of 3D scanning the implants on a horizontal surface, the impact of gravity on the implant in standing position was not considered, even though this has a huge impact on the final look post surgery.

In the next step, we explored the use of FEM to make the implant models hold a more natural shape, as they would in real world. We also generated 3D models of real implants based on the models sold by the company Johnson and Johnson, and 3D models of real patients based on a public access data set of breast cancer patients' MRI images. We developed a system to compare these two sets of models and rank the implants in terms of shape similarity to each patient model, suggesting the top two to a surgeon. Our results suggest that this system is able to choose implants similar to what human users would suggest, and potentially make the process of finding the best match of an implant more efficient by increasing the speed and decreasing the number of options that need to be considered.

Overall, our findings show that the pre-surgery planning process for breast reconstruction surgery can be improved by using AR for better visualization, and an automated method to find good matches during implant selection.

5.1 Future Work

The next step to determine the effectiveness of the developed methods is to model the whole catalogue of Johnson and Johnson implants to have a better variety of models to chose from, making the environment of our study closer to the real life conditions of the pre-operation decision making process. We also simplified both models by using only one type of material for the FEM modeling, which can affect the accuracy of our solution. With access to better computation devices, more accurate models can be generated to have even more realistic deformations and models.

There were also limitations caused by the COVID-19 pandemic, restricting our access to resources such as having plastic surgeons and mastectomy patients as the participating population of our user study. In order to compromise, we generated a visualization system to show the 3D models to participants who have the experience of working with medical images, and let them compare the models. A potential improvement can be generating patient models based on MRI images of patients who can be present for the comparison process, and running a study with surgeons as participants. As discussed in the first part of our research, it is also beneficial to have a mobile based AR application to show the suggested implant shapes as AR objects on the patient body, for better visualization and interaction with the model (see Figure 26).

If the information about the implant used for each patient is available as a database, it is also possible to use artificial intelligence and machine learning models to determine the best implant of choice.

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