Augmented Reality to Support Artery Localization in Breast Reconstruction

João Miguel Amaral Lopes
joao.amaral.lopes@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisboa, Portugal

October 2021

Abstract

The use of Augmented Reality (AR) in the medical field has been vastly studied and developed in the last decade to help healthcare professionals in surgical matters. However, limited evidence has been shown for the use of AR in breast reconstruction surgeries using deep inferior epigastric perforators (DIEPs). Such surgeries heavily rely on the use of computed tomography angiography (CTA) for preoperative imagery and, for professionals to make use of this data, a time-consuming manual task has to be performed. The purpose of this work is to understand if AR can aid users during the pre-operative and intraoperative processes of breast reconstruction surgeries using DIEPs, namely in locating the perforators and their tracing process, by reducing surgery time and increasing user satisfaction and communication. To validate these hypotheses, BREAST FLAPPAR - a user-centered ecosystem composed of AR systems, a report, and a data visualization for the operating room screens - was proposed. This prototype was designed to assist professionals during these procedures, relying on data from CTA imagery used as input for the AR systems and allowing surgeons to analyze crucial information in a simpler way than before. Informal observation and co-design sessions were conducted, together with a user study with seven specialists in this type of surgery to test the ecosystem. The results obtained indicate a reduction in the tracing process time of up to 95% and an overall 88% positive feedback in the satisfaction questionnaires. With these results, we can conclude that the ecosystem proposed can reduce surgery time and is useful for breast reconstruction surgeries using DIEPs.

Keywords: Augmented Reality; Deep Inferior Epigastric Perforator Flap; Breast Reconstruction.

1. Introduction

To perform microsurgery, in particular breast reconstruction using deep inferior epigastric perforators (DIEPs), all planning is crucial to increase the intervention's success and reduce possible errors [7]. It is important to acknowledge the fundamental role that preparation has on the surgery, together with the important role Computed Tomography with Angiography (CTA) scans play in this process [3]. Several methods have been previously developed for this type of surgery, such as using a Doppler ultrasound to identify perforators. Despite being helpful in this type of surgery, such technologies do not allow surgeons to obtain key information regarding perforators, leading to the widespread adoption of the CTA scan in breast reconstruction surgeries using DIEPs - a gold standard for this type of surgery [3]. The current model requires professionals to perform a slow manual task, consisting of tracing on the patient's skin the possible perforators' location using conventional markers and a ruler to use information obtained from the CTA scan. Two professionals are usually required to perform such task, with one surgeon reading the information from a non-graphical report and the other performing the tracing process. The lack of graphical elements and well-though data encoding presented in the current report, together with the iterative and long-lasting process, makes this task unnecessarily hard, leading to extended surgery time and subjectivity in the tracing process [1]. As the need for technological advancements increased within free flap transplantation, many systems focused on aiding the surgeon's navigation throughout the surgery were developed [2]. Throughout the years, a vast number of new technological systems have been developed within the different areas of medicine, with one area - breast reconstruction - standing out. The systems developed for this particular area over the years have achieved great results and have been quickly adopted by surgeons, even if facing some limitations. The main objective of this work is to verify if the use of an Augmented Reality (AR) ecosystem, together with a redesigned medical report, can help identifying and locating perforators in breast reconstruction surgery using DIEPs, ultimately aiming to reduce surgery time by eliminating manual tasks and creating a semi-automatic pipeline. Bearing this in mind, BREAST FLAPPAR was developed. These systems are capable of displaying vital information, allowing surgeons to analyze information about the identification, location and key characteristics of the perforators in a simpler way than before. A visualization where surgeons can instantaneously obtain qualitative and quantitative information through data encoding and graphical elements was also developed. This visualization will simultaneously be used to augment the patient space and as a relevant graphical (infovis) element to improve medical report reading. The ecosystem is composed by several elements, including a Spatial Augmented Reality (SAR) system that is able to project vital information regarding perforators on top of the patient's abdomen, a Mobile-AR application for iOS devices that allows professionals to analyze the same data directly on the patient's abdomen or any other surface, and an Optical See-Through Augmented Reality (OST-AR) system that merges CTA scan's data with a surface scan of the patient's skin, allowing healthcare professionals to analyze this vital information hands-free.

2. Related Work

Augmented Reality (AR) in medicine [8] fulfills the need to visualize and analyze medical data simultaneously with the patient and within the same space. This need drove professionals to build Medical AR systems such as ARM-PS [7] - a system that aims at being a simple mobile AR system that allows users to superimpose virtual information as a dissection route map, simply using their smartphones. To do so, the user needs to upload the three-dimensional imagery obtained from the CTA into the AR app, and by opening the camera, the virtual scene will be superimposed over the real-world. Furthermore, to increase the system's vessel location accuracy, the superimposed images are fixed to certain anatomical parts of the patient such as the umbilicus. To verify the accuracy of the ARM-PS, a study was conducted where the authors compared the results obtained from the system with the results obtained from a traditional handheld Doppler, using data from thirty patients and sixty inguinal areas. With this study, a correlation of 100 percent with the ARM-PS drawings and the location of the vessels and lymph nodes was identified. The authors were also able to verify that the flap harvest time, using ARM-PS, was 72 minutes, while the harvest time without using this new technology was 90 minutes, leading to an average time of harvest decrease of 20 percent. By defining a dissection route map in an easy, non-invasive, and more accurate way, ARM-PS is able to reduce surgery time while improving operative results, leading to a decreasing donor site morbidity.

Similarly to ARM-PS [7], another medical AR system [4] was developed, overlaying a vascular map on top of the patient using the CTA collected data in order to help guide surgeons prior to and during the perforator flap transplantation procedure. This new system was developed using ARToolKit, with the authors using screw-fixation markers as tracking tools for the system instead of using the umbilicus as an anchor to place the virtual scene. This method assures the fixation of the marker throughout the surgery, allowing professionals to trust the imagery projected and to not worry about possible displacements of the markers. The study conducted to understand the impacts of such technology within this surgery consisted of projecting the navigation system on top of an animal and measuring the system error. By analyzing the results obtained from this study, the authors were able to validate the success of the navigation system in identifying and projecting the correct caliber and location for each perforator. Furthermore, the navigation system obtained a mean error value of 3.474 mm ± 1.546 mm regarding the perforators' location. Even though further improvements and clinical trials need to be made, these initial prototype results validate the advantages that an AR navigation system can bring, such as precise navigation information displayed in real-time that allows a rapid and safe dissection of the perforators during a flap transplantation surgery.

It is important to explore other technologies within the Milgram's reality virtuality continuum [6] beyond the Mobile-AR technologies explored above, such as see-through AR. Gijs Luijten [5, 9] developed a see-through AR system, using Microsoft's HoloLens, that allows users to identify, locate and understand the intramuscular course of the perforators and epigastric arteries, which are crucial to the success of this medical procedure. By extracting data collected from the patient's CTA scan, and by using a marker placed on the abdominal nevi as a landmark for the system, the author was able to register an anatomy hologram for each patient, that can be used prior to and during the procedure. To guarantee the correct visualization throughout the procedure, real-time patient tracking can be obtained from the quick response marker attached to the abdominal nevi. The accuracy of this HoloLens system has been tested by conducting a study with twenty patients and two observers. From the 961 accuracy measurements conducted, 70 percent were below the clinically relevant threshold, meaning that the margin of error was less than 10 mm. Despite the limitations related with perceiving the depth of the hologram, the results obtained lead to the conclusion that a see-through AR system can be useful to display a patient's relevant anatomy for the free flap harvest procedure, leading to a more intuitive and accurate way compared to the regular model. It is also important to refer that further improvements and studies should be conducted to show that a system such as the one presented can be used to improve perforators localization and identification, and ultimately lead to a decrease in surgery time and in complications associated with this surgery.

As for SAR systems that help DIEP identification during a breast reconstruction procedure, a new system [3] was developed that allows users to visualize superimposed virtual images over the patient's abdomen. By using a video projector, information such as intramuscular course, perforating locations, and subcutaneous branching can be displayed prior to the surgery in order to provide visual aids to the user. Similarly to other AR systems such as ARM-PS [7], the umbilicus was used as an anchor for the superimposed images to guarantee their correct placement. To verify the accuracy of this new system, a study with nine patients was conducted, verifying the validity of the projected data collected from the three-dimensional reconstruction of the CTA by comparing it with data collected using a Doppler. Preliminary results showed that, by using Doppler ultrasound, 88 locations were marked, whereas the new system projected information regarding 100 perforators. More importantly, from the 34 perforators transplanted, the Doppler and the new system were able to find 19 and 29 locations, respectively. By comparing both methods, it is clear that the new system adds more important information to the users, such as intramuscular course and subcutaneous branching, while decreasing surgery time. Furthermore, by analyzing the study's results, the projection system was able to accurately identify more perforators than the Doppler. However, it is also important to mention that this system contains some limitations when it comes to the operator dependent method, which might lead to unaligned results [3].

3. Methodology

BREAST FLAPPAR is an ecosystem that was built to help surgeons and healthcare professionals involved in breast reconstruction surgeries using DIEPs. To reach the final visualizations, several tasks have to be performed, particularly in obtaining and manipulating the data. The first step in obtaining the data is to get preoperative imagery to access the location and information regarding the patient's perforators. In order to get this data, a CTA scan of the patient is performed, allowing us to obtain important information about the perforators such as location, caliber, intramuscular course, and subcutaneous course.

After obtaining the information generated by the CTA scan, this data will be used as input for the AVAOFF - an automatic system that analyzes the CTA scan's output and obtains crucial information regarding perforators. This system can fully eliminate the need for a radiologist team to perform the manual task of analyzing the CTA scan's results. AVAOFF's output is an XML file containing information regarding the patient's skin, fascia, umbilicus, and perforators. This file contains relevant information regarding to the perforators such as caliber, intramuscular and subcutaneous course, as well as its location. This information is cleverly described within XML tags and each entry of the file, inside the tags, corresponds to the location of a single point. This information allows us to accurately trace a three-dimensional detailed model of the patient's anatomy.

To obtain the 3D model, we need to convert this input information into 3D data. To perform such task, we developed a parser that starts by separating the data using the XML tags within the file, allowing the parser to generate specific meshes for each object. Each XML code line inside a tag is then converted into a point within a specific 3D mesh, allowing the creation of a complete 3D object representing a part of the patient's anatomy.

A python script was also created to define the umbilicus as the center of the model. The AVAOFF's XML output file defines the origin of the data as a point of the patient's anatomy that is not easy to detect using only the human eye. We decided to perform this translation in order to facilitate the calibration of the AR systems.

After performing some manual adjustments to the parser's output, the final 3D model (Fig. 1) is obtained, which will be used as input to all AR systems within BREAST FLAPPAR. This model contains a well-thought visualization composed of different elements such as the patients abdomen, umbilicus and perforators, allowing healthcare professionals to analyze this information efficiently and effectively.

For enhancing the visualization, and for calibration purposes, the OST-AR and Mobile-AR systems require as input the result of a merger between the 3D model and a surface scan. This surface scan contains the patient's body between the neck and the hip line, and is obtained by the doctors using a 3D scanner, particularly the Creaform go scan 3D. The result of the merging process can

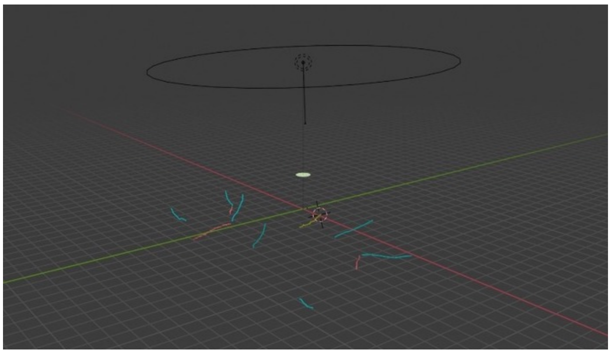

Figure 1: Blender dashboard during the 3D model's manual adjustments.

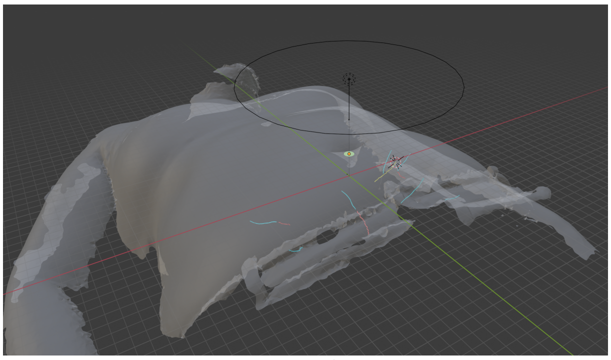

Figure 2: Visualization obtained after the merger between the 3D model and the surface scan, using Blender.

be visualized in Fig. 2.

The first AR system that we will approach in this work is the SAR system, which is able to project a well-thought visualization on top of the patient's abdomen (Fig. 4), allowing the surgical team to obtain an enhanced visualization containing information regarding the patient's anatomy, particularly the patient's perforators. This system allows all participants within the Operating Room (OR) to visualize the information displayed on the patient's abdomen, instead of limiting the visualization to the person who is holding or manipulating the device. To calibrate this system, the user needs to position the circle projected on top of the patient's umbilicus and align the curved lines with the patient's silhouette. By following these steps, the system assures that both the positioning and the depth of the projection are perfectly aligned with the patient. These elements allow professionals to intuitively understand how to align the visualization with the patient's body, but also to re-align during surgery if needed.

The second system within BREAST FLAPPAR's ecosystem is the Mobile-AR - an iOS application that allows healthcare professionals to analyze the patient's anatomy and important surgery information using only a smartphone, particularly, an iPhone. This system was created to be used in the OR and during the preoperative process, providing the user with an almost instantaneously automatic calibration that can be made on top of any flat surface or even on top of the patient's abdomen during surgery.

Figure 3: SAR system projecting the visualization during a simulated procedure.

Figure 4: User's visualization of the Mobile-AR system.

The portability of such a system should be valued since we are allowing professionals to prepare for a complicated surgery without the need for a special room or advanced equipment. By using this system, the team is able to perform the preoperative process in an innovative way. They are able to simultaneously be in any comfortable place chosen by them and still possess all the equipment needed for this process. Furthermore, this system assures that everyone in the team visualizes the same information as their peers, leading to an increase in communication between the team members.

The final AR system within BREAST FLAPPAR is the OST-AR system - an AR system made for surgeons to use during breast reconstruction surgery using DIEPs, using a smartphone and the Aryzon's headset. The visualization contains the 3D model explained above, as well as a 3D surface scan for increased visualization quality and calibration purposes. This scan creates a 3D mesh of the patient's body between the neck and the hip line.

Figure 5: Participant using the OST-AR system to perform a task during a simulated procedure.

During surgery, this system should be used by the surgeon as it provides a hands-free visualization that does not interfere with the normal surgery processes and tasks.

To calibrate the system, the user needs to align the model with the patient, which should be done by aligning the virtual body displayed in the headset with the patient's real body. The surgeon can move the model by using the touchscreen on the smartphone to manipulate its position and rotation. After the alignment between the model and the patient is completed, the model will be anchored in that position throughout the surgery. The final step in this process is to place the smartphone inside the headset and the visualization will appear instantaneously. After this process is completed, the surgeon will be able to visualize the information three-dimensionally anchored to the patient's body.

BREAST FLAPPAR also contains a report to be used during the pre-operative process, and a data visualization created for the OR's screens. Both data visualization elements contain important information about the patient, the perforators obtained from the automatic system (AVAOFF), and any observation/comments from the automatic system. This information about the perforators is within an easy-reading data table which contains the location, caliber, intramuscular course, and subcutaneous orientation. Furthermore, a data glyph was also added to each table entry, representing in a graphically way the relative location of each perforator. A graphical visualization representing the location of the perforators was also added in a very similar way to the visualization displayed by the SAR system. The graphical elements added to the data analysis tools within BREAST FLAPPAR assure a coherent experience between these elements and the AR system, leading to a seamless transition between elements within BREAST FLAPPAR's ecosystem.

4. Results & discussion

A user study was conducted to understand if the proposed ecosystem can enhance the pre-operative and intraoperative space. In this study, the main goal was to verify how helpful our work is regarding breast reconstruction surgery using DIEPs. This study was separated into two different phases, and took place in a simulated OR. The first focused on the pre-operative elements of our ecosystem, i.e. the report re-design and the Mobile-AR system, and was conducted during a pre-operative process using real patient's data. In this phase, we asked the users to perform some normal activities of this process using the elements within BREAST FLAPPAR developed for this purpose. After the users concluded this process, they were asked to fill in a satisfaction questionnaire, as well as answering open questions regarding their experience during a semi-structured interview. The second phase focused on the surgery, where the remaining elements of our work were tested, mainly the visualization developed for the OR screens, the SAR system, and the OST-AR systems. This phase was conducted during a simulated surgery with the same data used in the pre-operative study phase. Similar to the initial phase, we asked the participants to perform specific tasks, and after the conclusion of these tasks, they were asked to fill in a satisfaction questionnaire and answer some open questions during a semi-structured interview as well.

This study was conducted with 7 specialists with high experience in breast reconstruction surgery using DIEPs, being 71,4% male and 28,6% female. The participants have experience with breast reconstruction surgery with, on average, 13 years of experience, participating in over twenty surgeries, and regarding breast reconstruction using DIEPs, all participants have on average eight and half years of experience, with 71,4% having participated in over twenty surgeries, and 28,6% on less than ten surgeries of this kind. Regarding the users' experience with AR, 28,6% have experience with Mobile-AR, 42,9% with OST-AR, and 28,6% with SAR. The rest of the participants do not have experience with AR. Furthermore, 2 users (28,6%) have experience with OST-AR in pre-operative processes, and 1 participant (14,3%) have experience with OST-AR during an intraoperative process. The remaining participants do not have experience with AR in pre-operative or intraoperative processes.

4.1. Results

In our satisfaction questionnaires, we asked participants to answer each statement presented with a 6-level Likert scale, ranging from 1 (Strongly disagree) to 6 (Strongly agree). The results obtained in the satisfaction questionnaires can be analyzed in Fig. 6. The report section of the results obtained in this questionnaire showed us that the majority of the participants, in all statements, slightly agreed, agreed, or strongly agreed, particularly on average the participants answered positively for 81.63%. 85% of the participants answered that this report contains the most important information for the surgery and its preparation. These results allow us to understand that the report is useful when it comes to presenting and identifying the most important information to the pre-operative and intraoperative process. Furthermore, this report also provides an easy-to-understand analysis, while also improving communication between team members.

Regarding the data visualization created for the OR screens, similar positive results were obtained, where 97.62% of the answers were positive (4 or higher). Even though the same data and graphical elements are present in both the report and this data visualization, the latter scored significantly higher - all of the participants agreed or strongly agreed with 5 out of 6 statements presented.

In the Mobile-AR section of our satisfaction questionnaires, the answers were overall positive (87.76%). According to the results obtained, the participants believe that this system is particularly useful when it comes to the analysis of the patient's anatomy and its perforators, since 100% of the participants answered with agree or strongly agree to this statement. Furthermore, the 85% of the participants believed that this system is useful for the pre-operative process.

Similar results were also verified in the SAR section of the satisfaction questionnaire. In this section, 97.96% of the results were positive. More importantly, 100% of the users answered with a positive score for 6 out of the 7 statements presented. Furthermore, the users believe that this system is easy to learn, and is useful to the intraoperative process, since for both statements, 100% of the participants agreed or strongly agreed.

The last system approached in the satisfaction questionnaires was the OST-AR system, and obtained 75.71% of positive answers - the lowest score within our ecosystem. Nonetheless, the majority of the participants answered positively for all the statements, even if some statements obtained divisive answers, particularly when it came to how easy is it was to use the system, where 29% of the participants strongly disagreed that the system was easy to use.

After the satisfaction questionnaires, the participants also took part in a semi-structured interview were they were able to express their opinions and provide us important feedback regarding the elements that compose BREAST FLAPPAR. The feedback obtained in this part of our study regarding the report and the data visualization for the OR screen was very similar since both these elements contain the same information and graphical elements. Participants stated that the analysis of the information presented in both of these documents is very easy, and in the case of the report, better than the previous version. They have also mentioned that the use of graphical elements in both these elements improves significantly the data analysis, mainly since it provides the users with an efficient and quick way to obtain insights regarding the location of the perforators. Both these elements also received suggestions for improvement, mainly graphical changes in the interface presented. The changes suggested by the participants mostly represent the addition of small graphical elements such as the patient's silhouette in the representation of the perforators and the addition of labels in each point represented. Regarding the data glyph presented in each entry of the data table, some participants suggested that the line should be removed and replaced by a single point, since it can be misunderstood by the course of the perforator.

For the Mobile-AR system, the feedback was mainly positive, especially regarding on how easy it is to calibrate, use, and visualize the information presented in the system. The possibility to visualize advanced vascular structures within seconds with just a smartphone, as well as the reduction of the time spent during the pre-operative process, represent some of the feedback obtained. Following these ideas, the participants also stated that they did not felt any difficulties using the system and that they believed this system complements, helps, and should be used during the pre-operative processes. Two participants also suggested a change in the system, particularly the addition of the patient's fascia into the 3D model visualized.

When it comes to the SAR system, similarly to the results stated in the section above, the feedback obtained was very positive. The participants stated that the system provides the user with a quick calibration and easy-to-understand interface,

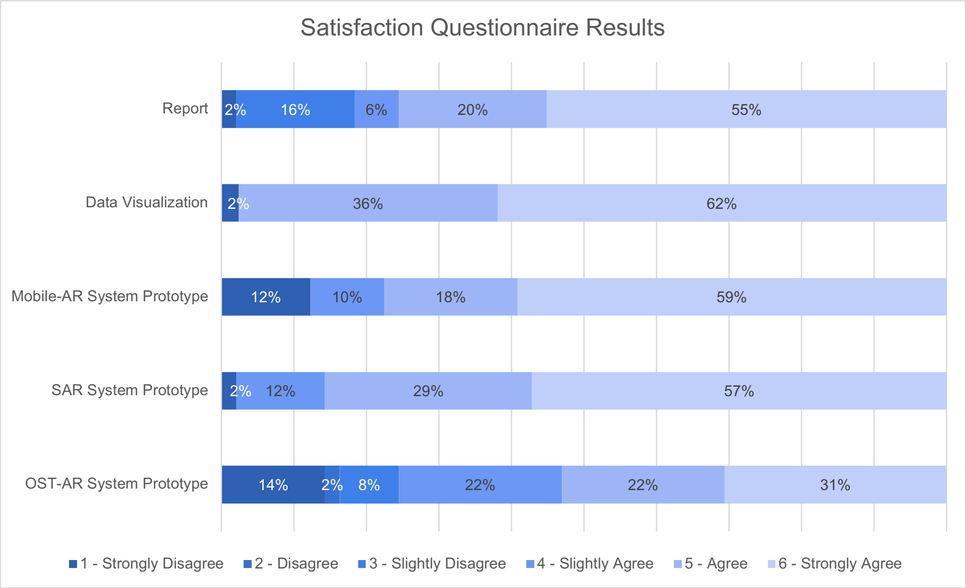

Figure 6: Results of the satisfaction questionnaires for each element of the BREAST FLAPPAR's ecosystem.

allowing a fast and simple tracing process. It was also stated this system complements the intraoperative space, and can and should be part of this process. Some changes were also suggested, particularly the addition of a section of the patient's muscle, for surgeons to understand how easy is to harvest a specific perforator. Furthermore, the participants also suggested to place the projector on the ceiling to increase the visualization's stability.

For the OST-AR systems, most participants participants started this part of the interview by explaining the problems they felt while using the system. They explained that the calibration of this system was hard, and re-calibration was needed in some situations. Furthermore, during the task, some visualization problems appeared to some participants such as flickering of the virtual scene, which according to the participants was uncomfortable, and in some particular situations a duplication of the virtual scene. Nonetheless, the participants also gave us positive feedback, mainly regarding the visualization where they stated that it contains the most important information while being easy to analyse, and also the importance of having a hands-free system.

Finally, the participants were also asked to explain what system they liked the most, and in what scenario. The vast majority of the participants answered with the SAR system for the intraoperative process and the Mobile-AR system for the preoperative process. Some participants only mentioned the SAR system in this question.

4.2. Discussion

As explained in section above, all the elements achieve positive results for every statement presented during the satisfaction questionnaires, particularly, the overall score obtained in the satisfaction questionnaires was 88.14% positive answers - a significantly high score for BREAST FLAPPAR. As stated previously the element in our ecosystem that scored the lowest was the OST-AR system, achieving 75.71% of positive answers. On the other hand, the SAR system achieved 97.96% of positive answers - the highest score obtained within BREAST FLAPPAR's elements. Regarding the feedback from the semi-structured interviews, we can understand that participants provided us with mainly positive feedback and comments. Further improvements were also suggested mainly regarding the addition of graphical elements such as a legend for each point in the report and data visualization, or the patient's fascia in the Mobile-AR system. These suggestions are important and can be implemented in the systems to increase the quality of the interface presented.

It is also important to mention that some participants, while performing the task related to the OST-AR system, found some issues mainly related to the calibration process and visualization. In some cases, the system needed recalibration if the user moved, leading to the need to re-calibrate the system, sometimes more than once. In some cases, it was also difficult to align the virtual scene with the real scene, making this process harder than needed. We believe that the calibration issues found during this procedure arose from the OR lights. Regarding the problems found in the visualization, some participants mentioned some flickering in the virtual scene, and a few experienced a duplication of the virtual scene. Even with these problems, the participants believe that this system is helpful to the surgery, and represents a good way to visualize the patient's anatomy to obtain insights for, and during the surgery.

These results allow us to conclude that the elements within BREAST FLAPPAR's ecosystem are useful and should be added to the current pre-operative and intraoperative processes.

During the tasks performed by the participants, no usage errors were found, although two participants struggled to understand the data glyph present in the report and data visualization, asking for help to understand this data encoding element. Furthermore, in the report, some participants struggled to understand the orientation of the graphical element.

Regarding the impact on surgery time, during our user tests, the participants took on average 12 seconds for calibration and 47 seconds for the tracing process using SAR system. With the OST-AR system, the participants spent on average 3 minutes in the calibration and 1 minute in the tracing process. Without using one of our AR systems, this process in a surgery lasts between 15 to 20 minutes, meaning the SAR system can achieve the same result in just 5% to 6,7% of the time usually spent. Regarding the OST-AR system, it represents between 20% to 26,7% of the time spent.

Furthermore, the vast majority of the participants found the SAR system to be the most helpful amongst the AR systems. By comparing the average time spent in calibration and tracing processes between the SAR and OST-AR systems, we can state that the SAR system represents the fastest choice for this task.

5. Conclusions

Our work intends to verify if an AR ecosystem can complement and enhance the current model of performing a breast reconstruction surgery using DIEPs, mainly when it comes to improving the manual tracing process and reducing surgery time.

The design process of BREAST FLAPPAR was always user-focused. To assure that our work fulfills the needs of healthcare professionals who will use these systems, we conducted an observation session of a breast reconstruction surgery to better understand their needs and its environment, which combined with our literature review, allowed us to define our initial ideas on how the prototype should be. After gather some more information, we conducted co-design sessions creating an iterative design process always with the help of our users, to reach the best possible solution to their needs. In these sessions, we received feedback on our prototype, as well as important suggestions that directly influenced the final product. A user study was conducted during a simulated pre-operative and intraoperative process with a real patient's data to directly evaluate our ecosystem in a closest as possible real-life scenario. These tests were conducted with 7 specialists, which were asked to perform specific tasks and then asked to fill questionnaires, participate in semi-structured interviews, and providing us with feedback and comments, allowing us to evaluate our work. The results stated in the previous chapter allowed us to understand that our AR systems are helpful to this surgery, and can also validate our hypothesis since it decreases surgery time and increases user satisfaction. Furthermore, it was also stated that BREAST FLAPPAR, through well-tough interfaces and data-encodings, increases the efficiency and communication between the members of the team, verifying our last hypothesis.

To conclude, after performing an analysis on the current market needs and by taking into consideration the results from the user study, we strongly believe that BREAST FLAPPAR is a next-generation system, ready for the future and to overcome any challenges that medicine might face over the next decades.

5.1. Future Work

Even though our work achieved remarkable results, there is still margin for improvement. Further studies should be conducted to gather more participants data. Regarding our SAR system, further improvements should be made, mainly by fixing the projector in the OR ceiling to increase stability. When it comes to our Mobile-AR system, the first limitation arises from being an iOS-only application. This application should also be made available to other operating systems, mainly Android. For the OST-AR system, further research should be conducted to mainly to understand if other technologies, such as the Microsoft's HoloLens, can achieve better results. A study to understand if AR markers improve the stability of the visualization should also be conducted. Finally, we believe that these systems can be applied to other medical procedures such as other breast reconstructive surgeries, other reconstructive flap-based surgeries, and even other types of medical procedures where it is helpful to visualize a virtual scene containing the patient's anatomy on top of the patient.

References

[1] R. J. Araújo, V. Garrido, C. A. Baraças, M. A. Vasconcelos, C. Mavioso, J. C. Anacleto, M. J. Cardoso, and H. P. Oliveira. Computer aided detection of deep inferior epigastric perforators in computed tomography angiography scans. *Computerized Medical Imaging and Graphics*, 77:101648, 2019.

[2] I. J. Cifuentes, B. L. Dagnino, M. C. Salisbury, M. E. Perez, C. Ortega, and D. Maldonado. Augmented reality and dynamic infrared thermography for perforator mapping in the anterolateral thigh. *Archives of plastic surgery*, 45(3):284, 2018.

[3] S. Hummelink, M. Hameeteman, Y. Hoogeveen, C. Slump, D. Ulrich, and L. S. Kool. Preliminary results using a newly developed projection method to visualize vascular anatomy prior to diep flap breast reconstruction. *Journal of plastic, reconstructive & aesthetic surgery*, 68(3):390–394, 2015.

[4] T. Jiang, M. Zhu, T. Zan, B. Gu, and Q. Li. A novel augmented reality-based navigation system in perforator flap transplantation—a feasibility study. *Annals of Plastic Surgery*, 79(2):192–196, 2017.

[5] G. Luijten. Holographic augmented reality in deep inferior epigastric perforator flap breast reconstruction. Master's thesis, University of Twente, 2020.

[6] P. Milgram, H. Takemura, A. Utsumi, and F. Kishino. Augmented reality: A class of displays on the reality-virtuality continuum. In *Telemanipulator and telepresence technologies*, volume 2351, pages 282–292. International Society for Optics and Photonics, 1995.

[7] N. Pereira, M. Kufeke, L. Parada, E. Troncoso, J. Bahamondes, L. Sanchez, and R. Roa. Augmented reality microsurgical planning with a smartphone (arm-ps): a dissection route map in your pocket. *Journal of Plastic, Reconstructive & Aesthetic Surgery*, 72(5):759–762, 2019.

[8] T. Sielhorst, M. Feuerstein, and N. Navab. Advanced medical displays: A literature review of augmented reality. *Journal of Display Technology*, 4(4):451–467, 2008.

[9] T. S. Wesselius, J. W. Meulstee, G. Luijten, T. Xi, T. J. Maal, and D. J. Ulrich. Holographic augmented reality for diep flap harvest. *Plastic and Reconstructive Surgery*, 147(1):25e–29e, 2021.