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BreLoAI - A Scalable Web Application for Breast Cancer Locoregional Treatment Approaches

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Abstract

Breast cancer is a disease with significant worldwide incidence and very high survival rates due to early detection and optimized treatments. Early detection allows more frequently the use of less radical systemic and locoregional treatments (i.e., surgery and radiotherapy). Offering patients less radical surgery (i.e., breast-conserving treatment with radiotherapy) or mastectomy with immediate reconstruction allows not only optimal cancer control but better quality of life due to improved aesthetic outcomes. However, 30% of the locoregional treatment results are still fair or poor. The assessment of the aesthetic results is a fundamental part of the treatment process and can be performed subjectively or objectively. The subjective assessment consists of the visual inspection of the patients' photographs after locoregional treatment by a panel of experienced clinicians who try to reach a consensus regarding the final evaluation. This process, however, is time-consuming and sensitive to the intrinsic biases of each panel member. Objective assessment methods appeared as an answer to these particularities. They rapidly progressed from measurements taken manually from the patient body to the extraction of features from the patients' photographs (e.g., the breast asymmetry, the change in skin tone, surgical scar visibility), with the support of computer vision algorithms, allowing the development of objective metrics to perform the aesthetic assessment. Naturally, with the advances in deep learning, the community is pointing their attention towards the training and deployment of these models applied to this use case. Software such as the Breast Analyzing Tool (BAT®) and the Breast Cancer Conservative Treatment Cosmetic Results (BCCT.core) integrate several computer vision algorithms to generate this cosmetic evaluation automatically. These frameworks, however, have the disadvantage of being offline applications, meaning that all the computational power requirements must be met by the user, thus imposing some limitations on their usage (e.g., installation, maintenance, and support). To overcome these issues, we propose a web-based solution capable of integrating these algorithms as web services, thus offloading the computational resources to a centralised server. To ensure that our application is scalable and capable of executing algorithms and processing data efficiently and effectively, we implemented a container-based architecture. Compared to the offline solutions already available, our proposal presents several advantages: 1) it is fully modular, allowing us to implement newer functionalities required by the clinical users; 2) it allows the registration of users from several institutions, thus promoting the creation of a multi-centre database and the cooperation between clinical communities focused on breast cancer locoregional treatment as a whole; 3) with the organic increase in the photographs database, our system is prepared to re-calibrate its machine learning algorithms, thus improving through time. All these details are transparent to the final user and will not jeopardise their experience while using the application. We believe that such a web application will streamline the work of clinical practitioners, promote seamless inter-center collaboration, and enhance the aesthetic evaluation of breast cancer locoregional treatments, ultimately improving patients' quality of life.

Categories: Health Informatics, Computer Vision, Web development
Keywords: user exeperience, breast cancer, human-computer interaction, user interfaces, artificial intelligence, machine learning

Introduction

Breast cancer (BC) is one of the most frequently diagnosed cancers worldwide, being the leading cause of cancer death in a significant number of countries. On the other hand, BC is also highly treatable, with a 10-year survival exceeding 80% in most high-income countries. This high survival rate powered the discussion and research on the survival aspects that have impact in long-lasting patient quality of life. The majority of patients usually undertake locoregional (LoRe) treatments (i.e., radiation therapy and surgery) which significantly impact their body image. For instance, in case of a poor aesthetic result, BC survivors will have to live with the potential disfiguring aesthetic consequences of their LoRe intervention [1]. In the last two decades, the community focused on the research of objective methods, often powered by

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artificial intelligence (AI) algorithms, to improve the quality of the aesthetic evaluation of BC LoRe treatment [2-10]. Cardoso et al. [11] evaluated the factors that determine aesthetic outcome after BC conservative treatment, and, more recently, Sampathkumar et al. [12] summarised the quantitative measures determined from breast images to objectively assess autologous fat grafting outcomes, and alerted for the importance of establishing standard protocols for quantitative measurements based on validated methods. Shortly after, Sampathkumar et al. [13] studied the effect of clinical (e.g., reconstruction type, laterality, timing of reconstruction, radiation therapy) and demographic factors (e.g., age, body mass index, race, and ethnicity) as predictors of postoperative symmetry, with the goal of contributing towards more informed decisions (made by patients and surgeons) about breast reconstruction surgery. Although being a lively discussion among the research community, consensus about the existence of a gold standard method for the aesthetic assessment of BC LoRe intervention outcomes is yet to be achieved.

Methods for the aesthetic assessment of BC treatment outcomes can be divided into subjective and objective. This assessment can be carried out on the patient or by means of photographs (e.g., prints, slides, or digital images), the latter being the preferable approach nowadays. Subjective methods include patient self-assessment and observer evaluation [14]. Patient self-assessment directly translates how they feel about their aesthetic result; however, its reproducibility is low, because it depends on several factors not amenable to quantification (e.g., age, socioeconomic status), which will affect how women see themselves after treatment. Observer evaluation is still widely used, allowing collaboration between different physicians, mitigating biases and increasing the confidence in the final result, assuming that observers have previous experience [15], and fairly reproducible when performed by experts working in different geographical areas, and that consensus is obtainable if a relatively low threshold of agreement is considered acceptable [16]. For instance, to understand how plastic surgeons assess breast morphology, Kim et al. [17] investigated the potential of eye-tracking technologies to document the patterns of their assessments, concluding that these technologies are useful for an in-depth analysis of the clinical assessment of breast morphology, and would be a valuable addition to current methods for evaluating surgical outcomes. Objective methods include manual, and semi-automatic [14]. Both types require the computation of several breast measurements, but, in semi-automatic approaches, a computer-aided framework usually takes place, reducing time and increasing precision.

Regarding computer-aided frameworks for the aesthetic assessment of BC treatment outcomes, we highlight two software applications: Breast Cancer Conservative Treatment Cosmetic Results (BCCT.core) [18] and Breast Analysing Tool (BAT) [19]. Developed by Cardoso and Cardoso [18], the BCCT.core software is desktop application that allows users to build an offline database of their patients (or studies) and includes a graphical user interface, to facilitate the interaction of users with the algorithms and the data. In parallel, Fitzal et al. [19] released BAT, which has similar functionalities. Using 2D digital photographs of the torso of the patients, these applications contain AI algorithms that support the user on computing breast descriptors and obtaining the aesthetic results. However, the use of offline software can be cumbersome and challenging due to issues such as installation problems, operating system incompatibilities, unmet hardware/software requirements, and the user's responsibility for maintenance.

Aiming to provide a solution to these challenges, we present a web-based solution that offers, at its core, an improved version of the functionalities provided by BAT and BCCT.core, with the advantage of being online and removing all the burden of the users' side (i.e., there is no installation process; incompatibilities with the operative system are not applicable, since the users only need Internet access and a web browser; the application and its algorithms run in a decentralised server with enough computing power, so hardware and software requirements is not a problem; maintenance of the software is the developers' responsibility). Besides the core functionalities, our software offers a new set of functionalities adapted to the advantages of moving to a web paradigm. In summary, we believe this work makes the following contributions:

(1) We propose two new web applications, BreLoAI Lite and BreLoAI, as alternatives to BCCT.core and provide a comparison between these three solutions;

(2) We explain, in detail, the architecture, database and algorithms implemented in the BreLoAI platform;

(3) We perform an algorithmic performance evaluation and conduct usability tests to assess the quality of our algorithms and users' satisfaction.

Potential users can access and use the platform through its publicly available website (https://breloai.inesctec.pt).

Materials And Methods

Algorithms for the aesthetic assessment of BC treatment outcomes

The computation of the aesthetic assessment of BC treatment outcomes often requires a feature engineering step to obtain several breast features based on asymmetry, scar visibility and skin colour. The following sections provide a literature review of the community's efforts concerning the design and development of algorithms that optimise or speed up these processes using 2D or 3D image data.

Algorithms for 2D Image Data

Detecting fiducial points of the breast (e.g., breast contour, nipples, sternal notch) is often a necessary step that precedes feature engineering. Motivated by the high time-consumption and low intra- and inter-observer agreement when evaluating subjective assessment of breast aesthetics using digital photographs, Udpa et al. [20] investigated methods to automate the localisation of fiducial points on anterior-posterior digital photographs (taken to document the outcomes of breast reconstruction), focusing on the nipple complex, given that the breast retraction assessment (BRA) (widely used to measure breast aesthetics) quantifies the symmetry of nipple locations. Although most works use anteroposterior digital photographs, there is also research on lateral views of the images. Kim et al. [21] devoted efforts towards the design of an objective measurement using breast ptosis based on ratios of distances between fiducial points manually identified in lateral and oblique views of clinical photographs. Lee et al. [22,23] proposed a quantitative measure of the lateral and inferior breast contour based on the catenary curve and demonstrated that it contains useful information about breast contour by using a mathematical predictive model, thus creating the possibility to help patients in deciding among their reconstructive options and to facilitate surgeons with surgical planning. This method was also effective when applied to 3D surface images of patients [24]. In a follow-up study, Lee et al. [25] extended this work by proposing a parametric active contour model for breast contour detection, showing that this mathematical shape constraint regulates the evolution of the active contour and helps the contour evolve towards the breast while minimising the undesired effects of other structures (e.g., areola, nipple and scars). Focusing on the detection of the breast contour, Cardoso and Cardoso [26] proposed a semi-automated approach that modelled the image as a weighted graph (based on the magnitude of gradients) and formulated the solution as the shortest path between the endpoints of the breast contour (annotated by the user). This approach was improved by Cardoso and Cardoso [27], which presented a fully automated method, where the endpoints of the breast contour are obtained by finding the strong contours between two regions of the torso. Later, Sousa et al. [28] extended these approaches by adding a priory knowledge of the mammary contour (shape prior), achieving better results than their predecessors. Cardoso et al. [29] extended these works, improved the automatic detection of the endpoints and reported a thorough evaluation of the performance of the proposed method against manually drawn breast contours. Silva et al. [30] were pioneers in moving these tasks into the realm of deep learning, by proposing a deep neural network architecture that uses iterative refinement during training to predict the key point coordinates of the sternal notch, nipples and breast contour, in an end-to-end fashion. Gonçalves et al. [31] extended the latter and added an image segmentation module to detect the breasts and to improve the quality of the regression of the breast contour keypoint coordinates. This problem has been recently revisited by Freitas et al. [32] who proposed the replacement Sobel filter (an edge detector) with a novel neural network solution to improve breast contour detection based on the shortest path, by learning effective representations for the edges between the breasts and the torso wall. Afterwards, Freitas et al. [33] designed a pipeline for full breast contour prediction, based on YOLOv9 [34], which reduces clinician workload and user variability for automatic aesthetic assessment.

The computation of fiducial points is a key step towards the engineering of asymmetry features. Dabeer et al. [35] present an automated method for computing the normalised BRA (pBRA), from routine clinical photographs taken to document breast reconstruction procedures. Dabeer et al. [36] developed algorithms to automatically detect the fiducial points of the umbilicus and the nipples, enabling the computation of a different version of the pBRA (pBRA2), essential to aesthetic assessment of BC surgery outcomes. Bui et al. [37] assessed breast symmetry following breast reconstruction using measures of distance (i.e., sternal notch to lowest visible point) and volume, and concluded that a higher percentage of the pre operative population had a higher distance symmetry, compared to post-operative, while post-operative patients had a volume symmetry comparable to the pre-operative group.

Another important line of research focuses on computing features related to scar visibility and skin colour. In this topic, we point the reader towards the work of Kim et al. [38] who proposed new measures of the appearance of surgical scars, obtained from digital photographs, that quantify the proportion of the breast area affected by scarring and the contrast between the scars and the surrounding skin, and showed their usefulness to quantify the aesthetic outcomes of breast reconstruction following skin-sparing mastectomy relative to those of breast reconstruction following conventional mastectomy.

Besides the detection of the breast fiducial points and the computation of important features, researchers have also focused on developing automated classifiers for BC aesthetic assessment outcomes. Cardoso et al. [39,40] used support vector machines (SVMs) to model ordinal relations present in the aesthetic evaluation classes of the BC conservative treatment and tested these approaches with different types of breast features (i.e., asymmetry, scar visibility and colour change). Oliveira et al. [41] extended this line of research, studying the replacement of an SVM with a radial basis function kernel by decision trees and linear SVMs, regarding their impact on accuracy, and found that the latter can serve as proper classifiers, with the advantage of being more interpretable. Shortly after, Oliveira et al. [42] worked on the use of lateral photographs of the patients to extract additional information about the volume of the breasts, along with an SVM-driven cascade generalisation classifier, and reported marginal performance improvements, suggesting that the integration of spatial and 3D information is beneficial to obtain robust models.

Algorithms for 3D Image Data

The potential benefits of integrating 3D data into the aesthetic assessment pipeline led Oliveira et al. [43] to develop a 3D model of a female torso to obtain a 3D aesthetic assessment of the surgical outcome. On a different perspective, Reddy et al. [44] used 3D metrics of breast cosmesis to compare two different fractionation regimens for whole breast irradiation. Research has also explored 3D fiducial point coordinate regression. For example, Kawale et al. [45] developed algorithms for automatically identifying key anatomical landmarks - such as the left and right nipples, sternal notch and umbilicus - from 3D torso images, achieving reliable localization results. Naturally, the richness of the multi-dimensional data, when properly combined, showed benefits. To help women make optimal decisions about breast reconstruction, Lee et al. [46] used 3D image and biometric data to power a case-based reasoning system that queries a database of women who have already undergone breast reconstruction surgery to retrieve a subset of cases that were pre-operatively similar to the current patient, and Oliveira et al. [47] devoted efforts to a solution that comprises RGB and depth information. They focused on detecting fiducial points supported by depth information and defining novel 3D image features that power an SVM-based cascade classification model that predicts the aesthetic outcome using 2D and 3D information.

Software applications for the aesthetic assessment of BC treatment outcomes

Cardoso and Cardoso [18] were pioneers in the development of automated methods for the aesthetic assessment of breast cancer conservative treatment (BCCT), aiming to achieve objective assessment methods, that could address the disadvantages of subjective evaluation. In this work, they used a dataset of images of patients, labelled by a panel of international experts into four classes (i.e., poor, fair, good, excellent), ensuring that only the images that reached a consensus among annotators were included in the final version of the dataset. To compute the aesthetic evaluation result, they extract three different feature sets: asymmetry, colour difference and scar visibility. In this paper [18], they released the BCCT.core Workstation software (the main precursor of the software described in this paper). The first release, a desktop application, allowed users to build their offline database and included a graphical user interface, allowing users to interact with the images and the algorithms. In addition, Cardoso and Cardoso [48] organised a workshop to evaluate the validity of the BCCT.core for the aesthetic assessment of the BCCT outcomes. They concluded that the software demonstrated consistent results, and had the potential to be the gold standard in clinical practice while enhancing collaboration among the research community. The release of this software application motivated researchers to study other dimensions of this field. For instance, regarding the type of photographies required to achieve an accurate cosmetic outcome, Cardoso et al. [49] concluded that since BCCT.core evaluation is based on more than just asymmetry, it combines enough information to accurately evaluate the cosmetic outcome based on the face-only photographic view. Given the increasing popularity of the software among researchers, Afonso et al. [50] conducted usability tests on BCCT.core. Contemporaneously, Fitzal et al. [19] developed the breast symmetry index, another objective method to assess breast aesthetics that assumes that if the operated breast does not differ in size and shape from the contra-lateral side, the symmetry is perfect and cosmetic outcome is good. Using digital photographs of the frontal and lateral views, along with a 2 × 2 cm large scale adjacent to the breasts for calibration, these calculations are performed with the aid of computer software, the Breast Analysing Tool (BAT). In a collaboration effort, Cardoso et al. [4] compared BAT and BCCT.core, concluding that including multiple parameters in the image analysis of BCCT aesthetic outcomes benefits the quality of the objective evaluation results. In addition, the authors also noted that photograph quality is crucial for the computation of other features besides asymmetry. Recently, there has been an interest in expanding the functionalities of these software applications (especially BCCT.core) and democratising their access to users worldwide. Hence, following the work of Cardoso and Cardoso [48], Gonçalves et al. [51,52] presented the prototype of a web-based version of the BCCT.core software. This preliminary version contained a database that allowed users to log in and authenticate in the system. Additionally, users could upload torso photos of the patients and organise this information using a simple graphical user interface. Regarding the information that one could extract from the images, this web application allowed users to run a breast keypoint detection algorithm to extract breast fiducial points necessary to compute the features used for the aesthetic classification; in this case, the system allowed the online calculation of the breast retraction assessment (BRA) [53]. The authors used Python and the Django framework [54] in the back end to facilitate the interaction with machine learning algorithms and developed the front end with HTML5, CSS and JavaScript (common languages for web development) to achieve a usable interface for users. The system also contained an administration panel. Gonçalves Rodrigues [55] extended the latter and built a fully workable web version of the BCCT.core, the WebBCCT.core. They started by conducting interviews with healthcare professionals to gather the requirements: after the elaboration of the interview script, they conducted a first round of interviews to get and validate the requirements; later, after the implementation of the back and front end, they asked the healthcare professionals for a second round of interviews to validate their implementation and to get feedback on the future steps and functionalities. After several benchmark tests, and given that the application required a flexible, and easy to manipulate, database, the chosen database technology of the WebBCCT.core application was MongoDB [56]. This application had an authentication system that allowed users to register using third-party applications (e.g., social media), and introduced the concept of teams: each user was associated with a healthcare institution. This change in the structure of the database allowed users to interact with peers of the same institution. Consequently, this required additional changes in the structure and organisation of the patient management pipeline: each patient was now associated with their biometric and clinical data. Following these changes, the authors had to come up with a new approach to manage the medical image data: users were allowed to upload, organise and group images by date. Besides this temporal organisation of the data, the system allowed users to automatically know other information (e.g., if an image was pre- or post-surgery, the time after surgery or the time after radiotherapy). While these changes allowed more freedom and flexibility for the users, the introduction of the teams, powered a better collaboration between them, enabling users to share clinical cases with their colleagues and benefit from each others' contributions to their analysis. After validating the database, workflow and user interface of this new web application, Rodrigues et al. addressed scalability and maintenance challenges to ensure the application could handle a growing database, integrate new services, and deploy updated machine learning models. Their solution involved containerizing the project using Docker, thus allowing continuously development and reproduction of previous results. Unsurprisingly, the development of software applications addressing challenges in this healthcare domain has inspired other researchers and institutions to create alternative solutions. For instance, Nicklaus et al. [57] created the "BreastDecisions" recommendation system, a framework adaptable to a particular clinical workflow that automatically suggests photographs of previous breast reconstruction patients, appropriate for counselling a given patient about appearance outcomes.

Software solutions for the aesthetic assessment of BCCT

This work builds on top of Gonçalves Rodrigues [55], who conducted interviews to establish the user requirements and implement the base features of the platform. Thanks to a close collaboration with clinicians (some of them co-authors of this paper), we updated the platform's requirements, added new tables to the database and changed some of the previous ones. In this section, we devote special attention to these updates. Currently, we have three applications to address this task: BCCT.core, BreLoAI and BreLoAI Lite. With these three alternatives, we provide a complete package of software that should satisfy the needs of all users. Table *1* shows all the differences between these three versions.

Application	Installation	Modality	Data Privacy	Maintenance	Computational Power
BCCT.core	Required	Offline	Data managed locally by the user	Manual	Provided by the user
BreloAI Lite	Not Required	Online	Data sent but not saved to a server	Automatic	Centralised in a server
BreloAI	Not Required	Online	Data sent and saved to a server	Automatic	Centralised in a server

TABLE 1: Different Software Solutions Applied to the Aesthetic Assessment Outcomes of BCCT, Developed by Our Team.

BCCT, Breast Cancer Conservative Treatment

BCCT.core

BCCT.core is the offline version of the software. With BCCT.core, the user has complete control over the data. On the other hand, they need to install the software in their local workstations, manage updates and provide the necessary computational power to run the algorithms. This application comprises two main features: breast contour annotation and aesthetic classification.

BreLoAI Lite

BreLoAI Lite is an online tool with similar use cases and features as BCCT.core, with the advantage of not requiring any software installation in local workstations, liberating the user from needing to meet the minimum requirements for running the algorithms. Moreover, this web application contains an algorithm that automatically detects breast contour fiducial points (i.e., the key points), which helps users annotate new data instances, thus reducing the manual labour required for labelling. BreLoAI Lite is ideal when users want to extract features or classify a reduced number of patients or when institutions can not upload and save their patient data in third-party (external) platforms or databases. In this web application, the user sends the patients' images to the backend to perform inference with the AI algorithms. To ensure patients' privacy, BreLoAI Lite does not save image data or any patient or inference information in the database at any point. After finishing their work, users can export the algorithm results to a CSV file and download it to their local workstations.

BreLoAI

BreLoAI is a fully fledged online platform that allows users to build their institutional repositories of patients by uploading their biometrics (e.g., age, height, weight), clinical data (e.g., surgery and radiotherapy information) and clinical images. This web application saves all the uploaded data in a dedicated database. We leveraged this database to train, develop and deploy new AI algorithms. BreLoAI comprises all the features of BCCT.core and BreLoAI Lite (plus the additional services or tools described in the following sections). Like BreLoAI Lite, BreLoAI is a web application, meaning that users do not need to worry about operating system (or device) compatibility, maintenance or local availability of computational power. In this version, we store all the patient data in a centralised server accessible through the Internet.

Architecture

The BreLoAI platform uses React [58] and JavaScript [59] for the front end, Django, Python and PostgreSQL [60] for the back end, nginx [61] (as a web server) for both the front and back end and Gunicorn [62] for multiple concurrent requests handling (essential for the deployment of the application in the production environment). Finally, we take advantage of Docker's portability, efficiency, isolation and scalability and containerise the back end, front end (see Figure *1*) and most modules (services). This kind of architecture offers several benefits, such as:

• Modularity and Maintainability: Separating the front end, back end, AI modules, and the database allows a modular approach to the development, which facilitates maintenance and updates in different parts of the application without impacting the whole system.

• Scalability and Performance: We can scale each part according to its specific requirements. For instance, if demand increases and we need to perform upgrades for the back end, these can be done without impacting the front end.

• Security: Having these layers in separate machines allows for increased security regarding the data saved in the database. For instance, the machine where the front end is running, with which users interact, does not store important data. Moreover, we can establish adequate communication channels between machines to increase the safety of the data.

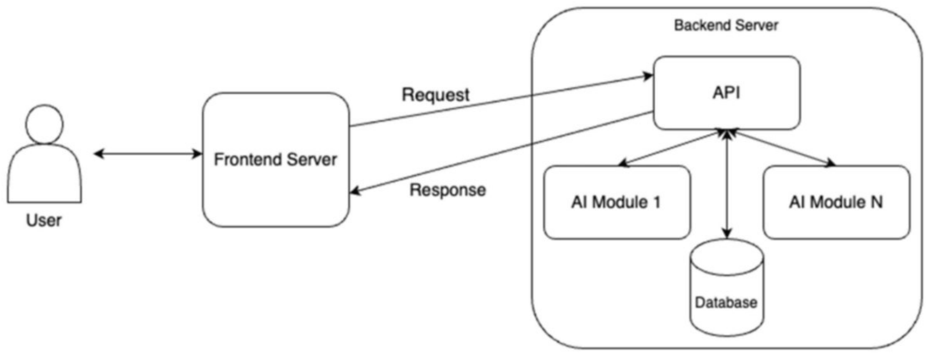


FIGURE 1: Architecture Diagram of the BreLoAI Platform.

The back and front ends have separated Docker containers that communicate with each other. The user interacts with the web page (i.e., front end), which sends requests through the API running in the back end. The back end fetches the database to retrieve the necessary information or communicates with the AI modules (running the algorithms), returning a response to the front end (which displays the information to the user).

Database

We developed the database using PostgreSQL since it is one of the relational database management systems (RDBMSs) that best integrates with Django, providing excellent reliability and scalability. Since the work of Rodrigues [56], we applied significant changes to the database architecture. An attentive look at Figure *2* shows that the BreLoAI database is more intricate and has grown in complexity, given the new use cases and functionalities required by healthcare professionals. We dissect these relations in the following sections.

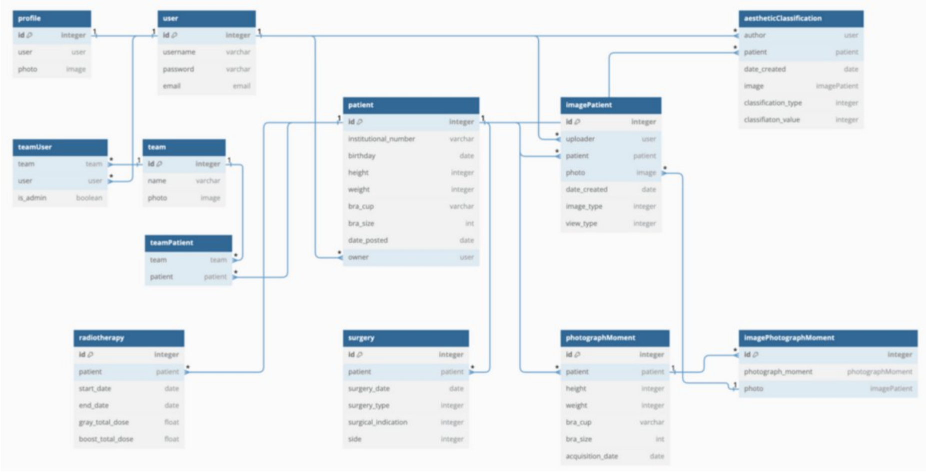


FIGURE 2: Database Diagram of the BreLoAI Platform.

Users

The public audience of the BreLoAI platform is healthcare professionals (e.g., nurses, surgeons or other physicians). In Figure *3*, we show the relations between the classes related to the Users. The user has a profile page that they can use to manage their accounts or add more personal information. Moreover, the user can upload various patients to the platform (each patient is owned by a single user) and make several aesthetic classifications (each classification belongs to a single user).

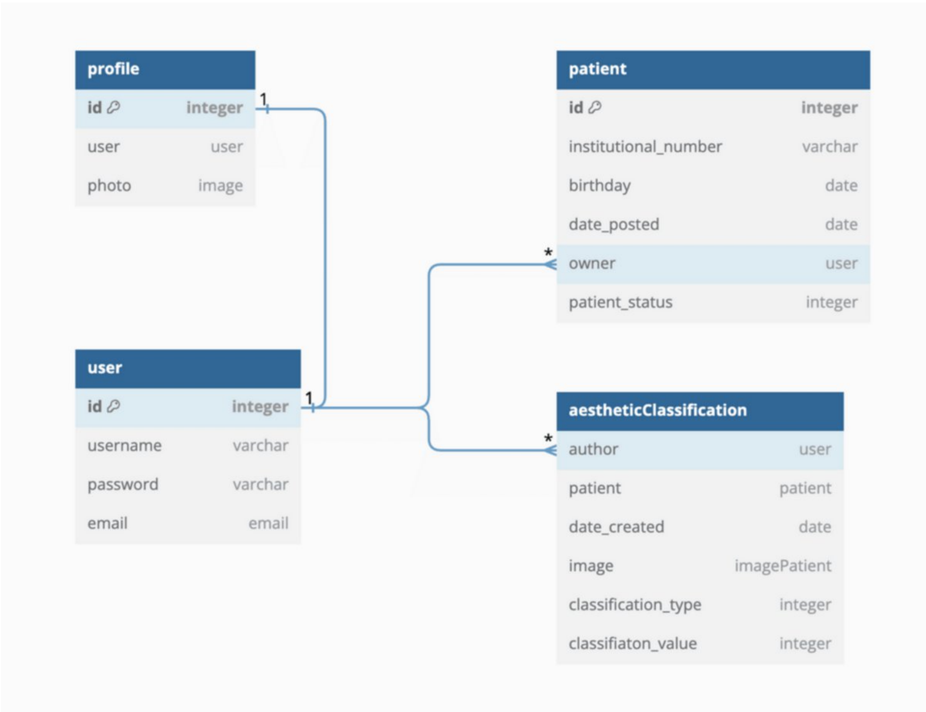


FIGURE 3: Database Diagram of the BreLoAI Platform: Users.

Patients

The development of the BreLoAI platform is centred on the patients (and their clinical photographs). For each patient, the user can record three events (see Figure *4*): photographic moments, radiotherapies and surgeries. A patient can have multiple surgeries. Each surgery stores the date (of surgery), the surgical indication (i.e., cancer, prophylactic or improvement), the type of surgery (e.g., conservative surgery) and the side of the body that underwent surgery (i.e., left, right or bilateral). Similarly, a patient may undergo multiple radiotherapy sessions. Each session records the start and end dates, total radiation dose and - if applicable - the total boost dose. Finally, a patient can have multiple photographic moments. Each photographic moment stores the date (of photographic acquisition), the patient's weight, height, bra cup, bra size and respective photographs (acquired on that date). Facilitating the tracking of changes in patient biometrics over time.

Each patient photo represents a different view of the patient (i.e., anterior, left, right, 45° left and 45° right). We use the anterior view to compute the aesthetic assessment score of the BC surgery outcomes. Moreover, since we can have photography acquisitions of the same view in a photographic moment, we ask the users to select the photo that BreLoAI should use to compute the scores (we refer to this photo as the representative photo of the patient at a photographic moment). For the aesthetic classification, the database stores the scores (i.e., Excellent, Good, Fair or Poor), classification type (i.e., objective or subjective), the user who made the classification and all the related data (e.g., breast fiducial points, features).

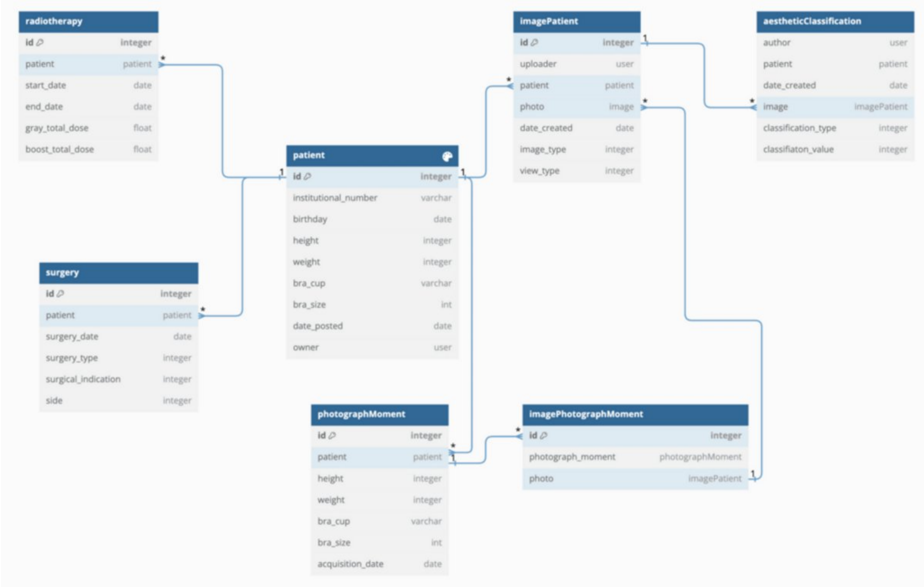


FIGURE 4: Database Diagram of the BreLoAI Platform: Patients.

Teams

The existence of teams (see Figure *5*) is a distinctive feature of BreLoAI since it allows many centres (e.g., hospitals and research institutions) to utilise the platform without sharing their data with other institutions. A team can have many users and patients. The team's users have automatic access to the team's patients. Users cannot access patients from another team unless they are also part of that team. This functionality allows members of the same team to collaborate easily on their cases. With this feature, BreLoAI facilitates multi-centre data gathering (i.e., we can build a repository with more heterogeneous data). This diversity of data will help us achieve more robust and reliable algorithms.

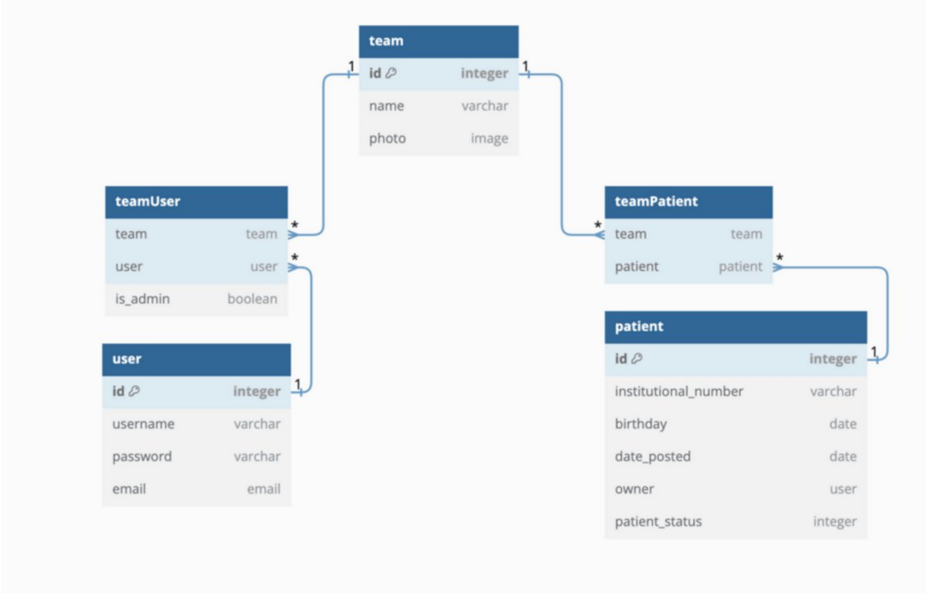


FIGURE 5: Database Diagram of the BreLoAI Platform: Teams.

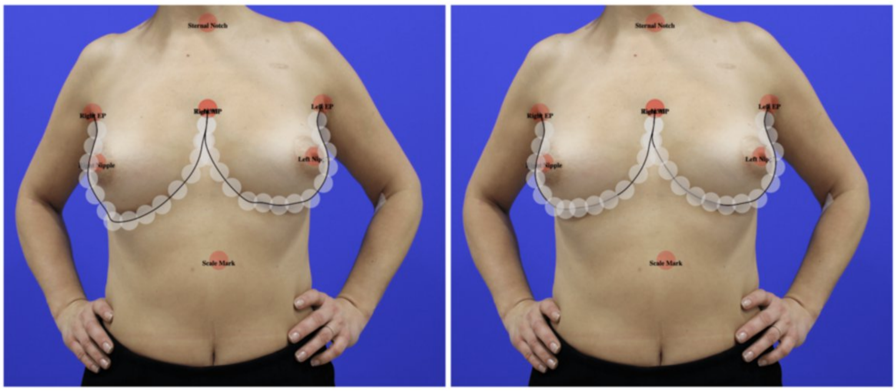
Main features

The transition of BCCT.core (offline) into BreLoAI (online) simplified the process of obtaining new annotations since a central database stores all the information. Hence, healthcare professionals can annotate new cases directly on the platform. Besides being automatically saved in the database, this information is readily accessible to researchers. This context prompted the development of different features (explained in the following sections).

Automatic Endpoint Detection

The calculation of the breast aesthetic score (more details in the sections below) requires the use of asymmetry and colour features (of the image). The computation of these features depends on a high-quality regression of the coordinates of the breast endpoints (i.e., the points closer to each armpit, the middle point for each breast and the location of the nipples and sternal notch) and the breast contour points. Essentially, we need to detect the breasts in the image to perform the aesthetic classification properly.

In BCCT.core, the user manually places the breast endpoints to get the breast contour points (semi-automatic approach). In BreLoAI, we deployed an automatic pipeline composed of an endpoint detection algorithm followed by a breast contour detection model. This upgrade allows users to reduce labour amount and time, even if they need to make minor corrections to the algorithms' outputs (see Figure 6).



(a) Initial automatic detection of the points. (b) Corrected automatic detection of the points.

FIGURE 6: Main Features of the BreLoAI Platform: Endpoints and Breast Contour.

The platform automatically generates an initial proposal of the fiducial points coordinates (a) the user can correct afterwards (b) by dragging the wrong points to the correct location.

Automatic Breast Contour Annotation

Each breast contour comprises 17 key points (2 endpoints and 15 control points) that must be in the correct location to ensure that the output of the aesthetic classification algorithm works as expected. When the user interacts with a photograph for the first time, the algorithm will output an initial proposal of the key points (see Figure 6) that the user can correct (if needed).

Automatic Aesthetic Classification

The main goal of BreLoAI is the automatic assessment of aesthetic outcomes of the BC surgery a patient has gone through. There are two types of classification: subjective and objective. The subjective classification is the clinical (individual) opinion of the user (i.e., the healthcare professional). The objective classification is the score of the algorithm that analyses a set of features (see Figure 7) extracted from the photograph (i.e., asymmetry and colour features; scar features are still in development). Although BCCT.core software already allowed users to obtain the objective classification, now they can also do a subjective classification and save it to the database. This allows us to continually evaluate and improve our algorithms by using subjective classifications as ground truth to train our (supervised) machine learning algorithms for the automatic aesthetic classification of BC surgery outcomes.

Dimension Asymmetry Features		Dimensionless Asymmetry Features	
BRA	2.18	pBRA	0.11
LBC	1.08	pLBC	0.05
UNR	0.84	pUNR	0.06
BCE	0.24	pBCE	0.04
BCD	0.09	pBCD	0.00
BAD	2.02	pBAD	0.02
BOD	20.08	pBOD	0.18

Colour Features		Scar Features	
cX2L	0.06	sX2L	None
cX2a	0.04	sX2a	None
cX2b	0.03	sX2b	None
cX2Lab	0.03	sX2Lab	None
cEMDL	0.58	sEMDL	None
cEMDa	0.13	sEMDa	None
cEMDb	0.12	sEMDb	None
cEMDLab	0.07	sEMDLab	None

Aesthetic Classification	Good	Scale (cm)	25.00

FIGURE 7: Main Features of the BreLoAI Platform: Automatic Aesthetic Classification.

The algorithm uses the breast contour keypoints to compute the features and then uses the features to calculate the aesthetic assessment score.

Areola Annotation

Although the main goal of BreLoAI is the automatic aesthetic classification of BC surgery outcomes, we can use the data or the machine learning models (deployed) to improve or develop tools to generate or annotate more data to refine our algorithms. For instance, we adapted the breast contour annotation tool to label the patients' areolas. This tool consists of 16 draggable points (eight per nipple) that the user can place to form the contour of each areola (see Figure 8). The platform automatically saves the coordinates in the database. Using this feature, we can gather more data about the breasts. Afterwards, we can use that data to train (validate or test) different algorithms, using it as ground truth annotations.

FIGURE 8: Main Features of the BreLoAI Platform: Areola Annotation.

The user can place the draggable points to form the contour of each areola.

Results

Algorithmic performance

As we stated in the previous section, the regression of the breast contour key points is key to successfully getting the aesthetic assessment of BC surgery outcomes (along with other data annotations that might be relevant for research). BreLoAI's breast contour detection pipeline contains two steps (each performed with a different model): breast endpoint detection and breast contour detection. In this section, we report the predictive performance of our algorithms by comparing their outputs with the ground truth annotations provided by the platform's users. Our breast endpoint detection algorithm consistently worked with 98% of the cases in the database and achieved an average error of 7.1% between the detected and the ground truth endpoints (see Table 2). The breast contour detection algorithm, which uses the output of the endpoint detection algorithm as input, also performed consistently, showing an average error of 2.89% between the detected and the ground truth contours (see Table 2).

Comparison	Key Points			
Endpoint Algorithm vs Ground Truth	Left Endpoint 16.25%	Middle Left Endpoint 5.2%	Middle Right Endpoint 1.66%	Right Endpoint 5.1%
Contour Algorithm vs Ground Truth	Left Breast Contour 2.67%		Right Breast Contour 3.1%	

TABLE 2: Average Error (%) Between the Algorithms' Predictions and the Ground Truth Annotations.

The first row presents the results for breast endpoint detection (left endpoint, middle left endpoint, middle right endpoint and right endpoints), and the second row presents the results for breast contour detection (left breast contour and right breast contour).

As soon as the breast contours are detected, the user must run the aesthetic classification to obtain the aesthetic scores (this algorithm uses the breast contours as input). This algorithm comprises two steps: feature extraction, which consists of extracting features from the image and breast contours (dimension and dimensionless asymmetry features, colour features and scar features), and aesthetic classification (poor, fair, good or excellent). We compare the results of the implemented algorithm (i.e., objective classification) with the ground truth annotations (i.e., subjective classification) by the users (see Table 3).

Surgery Type	Rank Difference						
	-3	-2	-1	0	1	2	3
Conservative	0%	0.31%	18.34%	61.32%	18.80%	1.23%	0%
All	0%	0.17%	14.02%	57.50%	26.05%	2.09%	0.17%

TABLE 3: Accuracy (%) of the Breast Aesthetic Classification Algorithm.

In the first row, include the discriminated results for the conservative surgery because the implemented version of the algorithm only used conservative surgery cases during its training. In the second row, we present the overall results for all types of surgery (i.e., all the cases available in the database). Rank difference captures how much subjective assessment deviates from the objective ranking, with 0 meaning perfect agreement.

Usability tests

The version of the database used in this paper contained over 1,000 patients. Fortunately, the processes of annotation, feature and aesthetic classifications rely on the aid of machine learning algorithms, allowing users to analyse a large database semi-automatically (if manually, this process would be time consuming and difficult). With BreLoAI, healthcare professionals only need to run and validate the algorithms for the patients they want to assess, having the option to manually refine the algorithm's predictions. This process takes, on average, 1 minute and 25 seconds (the fastest patient took 56 seconds to annotate and classify).

To evaluate the usability and user experience of the platform, we provided a questionnaire to six healthcare professionals from foreign institutions and ensured these users were interacting with the platform for the first time. The evaluation consisted of three parts: task performance evaluation, heuristic evaluation and the System Usability Scale (SUS) evaluation.

Task Performance Evaluation

We provided the clinicians with a set of tasks, which reflect the pipeline to annotate and classify the photographs of a patient:

(1) Add a patient to the platform;

(2) Add a photographic moment to the record of the patient and upload photos;

(3) For each photo, choose its “View Type”;

(4) Choose which image to annotate and classify;

(5) Annotate and classify the image;

(6) Add surgery information to the record of the patient;

(7) Add radiotherapy information to the record of the patient.

We found that the users completed most tasks without issues (see Figure 9 for a summary of task completion). Overall, users completed 90% of the tasks easily and 5% hardly, but with success. We noticed that only 5% of the tasks remained uncompleted. We also highlight some of the difficulties reported by users in specific tasks:

• Task (2) - one user found it hard to complete this task;

• Task (3) - one user stated this task was difficult, and another could not complete it;

• Task (5) - one user could not complete this task.

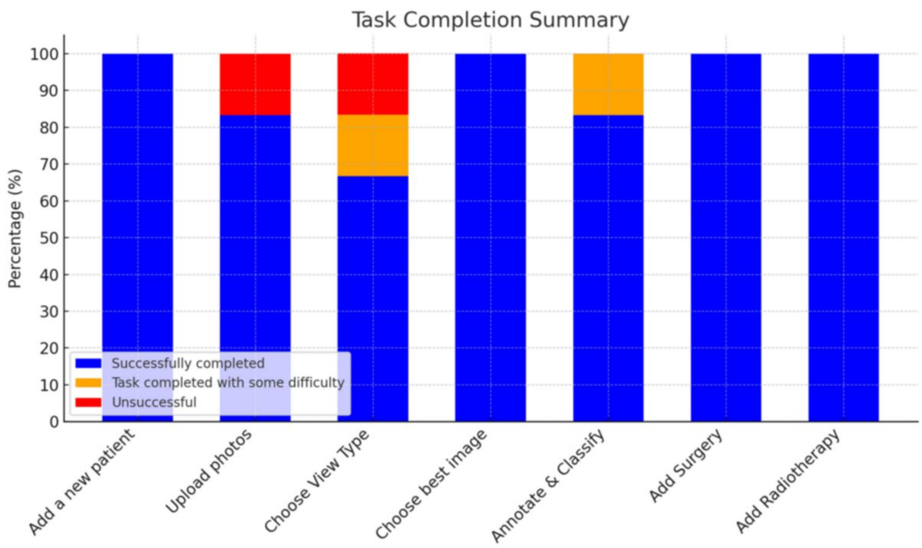


FIGURE 9: Usability Tests: Task Performance Evaluation.

This bar plot presents the summary of the task completion (by users), divided into three categories: successfully completed, task completed with some difficulty and unsuccessful.

Heuristic Evaluation

In this part of the questionnaire, we asked the clinicians to assess the platform based on widely recognised usability principles (chosen by us):

• Match between system and the real world - if the terminology used in the platform correctly represents the terminology used routinely by the user;

• Recognition rather than recall - if the user interface is easy and intuitive to use;

• Help users recognise, diagnose and recover from errors - if the interface gave sufficient feedback to identify and overcome the issue in case an error appears;

• Flexibility and efficiency of use - if the platform is responsive and pleasing.

Overall, the users agreed with all these heuristics and found the platform easy and pleasant to utilise.

There are some small areas that can be improved, such as design choices and poor wording in very specific cases (see Table 4).

Heuristic	Number of Issues	Example of Issue
Match between system and the real world	2	Consider changing “plot” to “annotate”
Recognition rather than recall	1	Would create some buttons on top of the page that will make it easier to navigate between the screens
Help users recognise, diagnose and recover from errors	0	Not applicable
Flexibility and efficiency of use	0	Not applicable

TABLE 4: Usability Tests: Heuristic Evaluation.

This table presents the issues identified by the users (quantity and examples) per heuristic type.

System Usability Scale Evaluation

We used SUS to capture the overall perception of the platform’s usability. Following SUS guidelines, we asked users to rate their agreement with 10 statements on a scale of 1-5. Our platform obtained an average SUS score of 90.83, indicating a very good overall experience regarding user usability and experience. After analysing the questionnaire results, we observe that users are happy with the platform, showing strong usability scores and a high task completion rate. Even though we need to implement some minor changes, it is clear that the platform has the potential to streamline clinical workflows and contribute to research efforts.

Discussion

With the development of the BreLoAI platform, we can demonstrate the potential and benefits of bridging the gap between healthcare professionals and researchers by streamlining the annotation and data collection process. Our software presents solutions for key challenges in medical image analysis in the form of various algorithms and provides tools to gather high-quality datasets for the development of new robust and reliable algorithms. By leveraging a simple and user-friendly interface and data management features, BreLoAI allows clinicians to provide their expertise effectively and enables researchers to access well-curated datasets. With its intuitive design, the integration of various tools tailored to clinical workflows and our modular approach, based on APIs, we ensure that healthcare professionals can focus on the medical content without being burdened by technical complexity. Moreover, features such as multi-institution collaboration and the ability to connect our algorithms to external entities enable researchers to collect, organise and analyse data from various sources.

Conclusions

Future work can involve the development and implementation of new features for the evaluation and validation of AI tools and the implementation of mechanisms to automate the training and testing of the AI modules as new data is gathered. With continuous effort in the development and adaptation of the BreLoAI platform, we believe it can play a key role in advancing research, ultimately contributing to better outcomes for the patients.

In conclusion, the BreLoAI platform aims to bridge the gap between the clinical and technology contexts. By addressing the specific needs of both groups, we contributed to the foundation for more efficient workflows and enhanced data quality. Finally, this effort highlights the importance of technology and AI in promoting innovation in healthcare.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

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