VISION-BASED FLAP PLANNING SOFTWARE TOOL FOR RECONSTRUCTIVE FACIAL PLASTIC SURGERY

by

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A thesis submitted in conformity with the requirements for the degree of Master of Health Science
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Abstract

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The success of reconstructive facial plastic surgery is determined not only by the treatment of the given pathology but also the restoration or maintenance of normal morphological features and the reduction of scarring. Failure to consider these aesthetic components can have significant negative psychological effects for the patient. A vision-based approach to automatic lesion segmentation and incision planning is proposed. Optical camera images of the face will be analyzed for lesions and estimated lines of relaxed skin tension using feature-based registration. Simulation of stresses within wound closures will consider skin mechanical properties and craniofacial structures to implement a constitutive model for finite element stress analysis. The objective of this research is to develop a consistent and effective approach to flap planning for reconstructive facial plastic surgery. This system has applications for surgical training, surgical automation and control, and the improvement of patient care through the reduction of treatment variation.
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# Contents

1 Introduction 1
   1.1 Research Motivation ................................................. 2
      1.1.1 Surgical education .............................................. 2
      1.1.2 Patient outcome ................................................. 2
   1.2 Research Goal ......................................................... 3
   1.3 Research Objectives .................................................. 3
   1.4 Project Overview ...................................................... 4

2 Background & Literature Review 5
   2.1 Surgical flaps ......................................................... 5
      2.1.1 Linear closure ..................................................... 5
      2.1.2 Rhomboid flap ..................................................... 7
   2.2 Relaxed skin tension lines ........................................... 7
   2.3 Aesthetic units ......................................................... 9
   2.4 Facial landmarks ....................................................... 10
   2.5 Finite element method ............................................... 10
   2.6 St. Venant’s Principle ............................................... 11
   2.7 Skin tissue modelling and mechanics .................................. 11
   2.8 Plastic surgery simulation ........................................... 12
   2.9 Automated lesion segmentation ..................................... 13
      2.9.1 Non-rigid registration ............................................ 13

3 Methods 14
   3.1 Commercial software .................................................. 14
      3.1.1 Matlab ............................................................... 14
      3.1.2 COMSOL Multiphysics ............................................. 14
      3.1.3 SolidWorks .......................................................... 14
   3.2 Graphical user interface (GUI) ........................................ 14
   3.3 Patient image data ...................................................... 15
   3.4 Lesion segmentation .................................................... 15
   3.5 Automated facial landmark detection ................................ 16
   3.6 Relaxed skin tension line (RSTL) mapping ............................ 17
   3.7 Finite element analysis (FEA) ......................................... 17
      3.7.1 Overview ............................................................ 18
3.7.2 Surgical flap geometry .......................................................... 18
3.7.3 Patient face geometry ......................................................... 19
3.7.4 Patient-specific, non-rigid registration ................................. 19
3.7.5 Geometry assembly ............................................................. 20
3.7.6 Meshing .............................................................................. 21
3.7.7 Skin tissue constitutive model ............................................ 21
3.7.8 Dermal layers ..................................................................... 22
3.7.9 Aesthetic regional units ..................................................... 22
3.7.10 Fixed constraints ............................................................... 23
3.7.11 Wound closure .................................................................. 23
3.7.12 Accuracy vs. Computation time ........................................... 23
3.8 Visualization & User verification .............................................. 23

4 Results ................................................................................. 24
4.1 Graphical user interface (GUI) ................................................ 24
  4.1.1 Patient image acquisition ................................................. 24
  4.1.2 Relaxed skin tension line estimation .................................. 25
  4.1.3 Wound geometry selection .............................................. 25
  4.1.4 Visualization & User verification ....................................... 27
4.2 Automated facial landmark detection ...................................... 28
4.3 Relaxed skin tension line estimation ....................................... 28
4.4 Finite element analysis (FEA) .................................................. 29
  4.4.1 Fusiform wound closure in square tissue region ............... 29
  4.4.2 Rhomboid flap closure in square tissue region ................. 31
  4.4.3 Fusiform wound closure in human face ............................ 32
  4.4.4 Rhomboid flap closure in human face ............................... 33

5 Discussion ............................................................................ 35
  5.1 Results of automated facial landmark detection ..................... 35
  5.2 Relaxed skin tension line estimation ..................................... 35
  5.3 Results of FEA of surgical flaps ............................................. 35
    5.3.1 Linear closure ............................................................... 35
    5.3.2 Rhomboid flap ............................................................. 35
  5.4 Future work ......................................................................... 36
    5.4.1 Validation ................................................................. 36
    5.4.2 Flap geometries ........................................................... 36
    5.4.3 Portability ................................................................. 36
    5.4.4 Wound interaction with aesthetic regional units ............ 36
    5.4.5 Image morphing ......................................................... 37
    5.4.6 User interface ............................................................ 37
    5.4.7 Relaxed skin tension line field ...................................... 37
    5.4.8 GUI for design of arbitrary CAD flap geometry .......... 37
    5.4.9 Patient image modalities ............................................. 37
    5.4.10 Extension to other regions ......................................... 37
List of Figures

1.1 Examples of surgical flaps on the face with initial incision lines (left) and final closure lines (right) [2]. ............................................ 1
1.2 Example of highly visible facial scar [11]. .................................................. 3
1.3 Overview of project .................................................................................. 4

2.1 Examples of different types of flap geometries [13]. ................................. 6
2.2 Fusiform wound (left) and its closure (right) [2]. ........................................ 6
2.3 Closure of a rhomboid (Limberg) flap illustrating a) initial wound and excisions, b) flap mobilization and closure, and c) final lines of closure [2]. ........................................ 7
2.4 Basal cell carcinoma resection of the forehead with rhomboid flap closure [13]. ........................... 7
2.5 Relaxed skin tension lines drawn on patient [15]. ..................................... 8
2.6 Z-plasty with a) correct design that aligns with relaxed skin tension lines and b) with incorrect design that crosses several relaxed skin tension lines (bottom) [15]. Note that initial incisions are indicated to the left of the arrow, and final closure lines are indicated to the right of the arrow ........................................ 8
2.7 The use of a fusiform wound to align a small scar with relaxed skin tension lines [15]. .......................... 9
2.8 Aesthetic units of the a) face, b) anterior view of nasal subunits, and c) lateral view of nasal subunits [2]. ........................................... 9
2.9 Example of 26 craniofacial landmarks [26]. ............................................ 10
2.10 Discretization of a domain into a set of basis functions for a one-dimensional displacement function (left) and a three-dimensional stress analysis of a wheel (right) [28]. ............... 11

3.1 Tasks-constrained deep convolutional neural network architecture for automatically detecting facial landmarks [19]. ........................................ 16
3.2 Template of relaxed skin tension lines to be fit to patient image ......... 17
3.3 Image warping of template RSTL image onto patient image ................. 18
3.4 CAD representations of a fusiform wound (left) and rhomboid flap (right). .................................................. 19
3.5 Three-dimensional mesh to be used as template for FEA [54]. ............... 20
3.6 Fusiform wound left and rhomboid flap (right) geometries added to patient face geometry. ................. 20
3.7 Domain partitioning of patient face template geometry for varying elastic properties with elliptical wound (red). ........................................... 22

4.1 GUI: Patient image acquisition ............................................................... 24
4.2 GUI: Relaxed skin tension line display ................................................ 25
4.3 GUI: Wound geometry selection for a fusiform closure: initial wound placement (top), rotation and scaling of wound (middle), and approximate lines of closure (bottom). 26
4.4 GUI: Wound geometry selection for a rhomboid flap: initial wound placement (top) and approximate lines of closure (bottom). 27
4.5 GUI: Visualization of final lines of closure as estimated by FEM. 28
4.6 Automated facial landmark detection results using Zhang, Luo, Loy, et al.'s method [19]. 28
4.7 Relaxed skin tension line estimation results. 29
4.8 Meshes used to generate an FEA solution for fusiform wound closure: initial mesh (left), mesh after adaptive refinement (right). 29
4.9 Von mises stress in a fusiform wound closure in a square region of tissue. The white line indicates the final line of closure. 30
4.10 Displacement in z-direction (out of plane) in a fusiform wound closure in a square region of tissue. 30
4.11 Meshes used to generate an FEA solution for rhomboid flap closure: initial mesh (left), mesh after adaptive refinement (right). 31
4.12 Von mises stress in a rhomboid flap closure in a square region of tissue. The white line indicates the final line of closure. 31
4.13 Displacement in z-direction (out of page) in a rhomboid flap closure in a square region of tissue. 31
4.14 Von mises stress in a fusiform wound closure in a full human face geometry. The while line indicates the final line of closure. 33
4.15 Von mises stress in a rhomboid flap closure in a full human face geometry. The while line indicates the final line of closure. 34
Chapter 1

Introduction

A surgical flap is a portion of tissue that is moved from its original location to another site [1]. The defining trait of a surgical flap is that it is able to maintain its own blood supply, which can be contrasted with a surgical graft that relies completely on the blood supply at its transplanted location [1]. Surgical flaps are used extensively in plastic and reconstructive surgery and are fundamental to the success of plastic and reconstructive surgery procedures that require the closure of a wound [1]. An example of several flaps can be seen in Figure 1.1.

Figure 1.1: Examples of surgical flaps on the face with initial incision lines (left) and final closure lines (right) [2].

Competent surgical flap planning can pose difficulties to surgeons for several reasons:

- It is difficult to visualize final flap positions and relaxed skin tension lines.
- It is difficult to identify compounding stresses and interactions between different aesthetic regional units.
• There are significant differences in skin characteristics between different patient populations based on age, ethnicity, etc.

• There is a wide selection of available surgical flap geometries to correct a given pathology. Often, surgeons revert to a given subset of available geometries based on familiarity.

The goal of reconstructive plastic surgery of the head and neck is both functional and aesthetic in nature [3]. The highly visible nature of the surgical region of the face necessitates optimal results in terms of minimizing scarring. If scarring is not reduced, serious psychological trauma and social anxiety can result [4,5]. Many hours of surgical training are required to achieve optimal results [7]. This poses a challenge for surgical trainees with an insufficient number of hours in the operating room [7].

It is proposed that a vision-based, finite element analysis approach for surgical flap incision planning be developed. The developed system will perform patient-specific modelling of surgical flap closure, assisting the user in selecting appropriate flap types and placement to correct the pathology based on the determined size and shape of the necessary closure, the location of lines of relaxed skin tension, and the reduction of stress in the final closure. Optical camera images of the face will be analyzed, estimating lines of relaxed skin tension using feature-based registration. Modelling of stresses within wound closures will consider skin mechanical properties and craniofacial structures.

The objective of this research is to develop a deterministic and effective approach to flap planning for reconstructive facial plastic surgery. This system has applications for surgical training and surgical automation and control. It is the hope of the author that this system can ultimately improve patient care through the improvement of flap selection and reduction of treatment variation.

1.1 Research Motivation

1.1.1 Surgical education

The field of facial reconstructive plastic surgery requires many years of training to obtain expertise [7]. Though current medical education is extremely structured and rigorously accredited, it has not changed significantly since the beginning of the twentieth century [8]. Due to the nature of both financial costs and the increased demands of modern surgical training and specialization, surgical education has recently been shifting from an apprenticeship-based model to a deterministic, objective-based model [7]. Consequently, new technology must be developed to allow surgical trainees to improve patient outcome without significant added cost to the healthcare system [8].

In 2004, the American Surgical Association recommended that new teaching technologies be incorporated into surgical education so that surgical trainees could acquire necessary skills outside of the operating room before beginning to operate on patients [8]. Surgical simulation is a technology that clearly facilitates this goal. Simulation is an accepted tool in the domain of plastic surgery education and has been achieved with various animal, cadaver, and bench models, but it is only recently that computer simulation has been able to provide significant benefits to surgical training [7].

1.1.2 Patient outcome

Plastic and reconstructive surgery are very much concerned with aesthetic component of restitution. Scarring or deformity introduced by surgical intervention can cause significant psychological trauma in
the affected patients. This is especially true in the region of the face, since humans are particularly sensitive in their perception of facial features and thus deformities [6].

A study by Lawrence, Fauerbach, and Thombs of 346 individuals with burn scarring showed statistically significant correlation between scar visibility and severity with body-esteem in individuals who held physical appearance with high importance. Brown, McKenna, Siddhi, et al. performed a study on the quality of life of 34 scar patients and found that scar severity and location were correlated to feelings of anxiety, stigmatization, sociability, confidence, and compensating behaviours [4]. Bock, Schmid-Ott, Malewski, et al. found similar results when studying the effects of scarring on the quality of life in 100 individuals [5]. For example, some individuals expressed fear that their scarring would affect their perceived employability, and some experienced greater difficulty in communicating and making eye-contact during conversation [5].

Figure 1.2: Example of highly visible facial scar [11].

1.2 Research Goal

To assist with surgical training and patient outcome by modelling surgical outcomes preoperatively and providing information and feedback on important variables associated with surgical flap closure.

1.3 Research Objectives

It is the objective of this project to create a software tool that can model the mechanical behaviour of the closure of surgical flaps at a patient-specific level. This tool is intended to automatically determine craniofacial landmarks that will allow for automated plotting of relaxed skin tension lines. This tool will act as an aid for surgical education, planning, and potentially automated surgical guidance. The project will achieve the following goals:

- Segment lesions in a semi-automated fashion
• Automatically plot relaxed skin tension lines (RSTLs)
• Allow the user to define desired lines of incision and closure
• Simulate the resulting stresses and strains in the skin tissue based on the previously defined lines of incision and closure
• Visualize final tissue displacements after closure
• Provide the aforementioned data at a patient-specific level
• Allow for user input to account for variances between simulations and measured patient characteristics

1.4 Project Overview

The method by which this tool will function can be broken into several components. The steps can be seen in Figure 1.3. Each of these components will be discussed in further detail.

Figure 1.3: Overview of project
Chapter 2

Background & Literature Review

2.1 Surgical flaps

A surgical flap is a portion of tissue that is moved from its original location to another site with the purpose of closing a wound [1]. The surgical flap is distinct from a surgical graft in that it is able to maintain its own blood supply from its original donor site [1]. Surgical flaps are used extensively in plastic and reconstructive surgery and are fundamental to the success of plastic and reconstructive surgery procedures that require the closure of a wound [1].

The use of surgical flaps has been recorded as early as 600 BC [1]. Major advances in surgical flap techniques were made through the courses of World War I and II [1, 12]. Modern flaps are signified by the variety of blood supplies available in their design in comparison to early flap techniques [1].

Surgical flaps can be further classified into two groups: local flaps and distant flaps [2]. Local flaps involve the transfer of tissue between anatomically contiguous sites, whereas distant flaps involve noncontiguous sites [1]. Additionally, surgical flaps can be classified by their blood supply, being labelled as:

- **random**: blood supply is not from a named artery but rather comes from the dermal and subdermal plexus,
- **axial**: blood supply comes from a specific, named artery or group of arteries
- **island**: vessels supplying blood also act as the only attachment of the flap to its original donor site [1, 2].

Finally, flaps may also be classified by their geometry and dominant method of wound closure: advancement, interpolation, rotation, and transposition [1].

An example of several surgical flap geometries can be seen in Figure 2.1.

2.1.1 Linear closure

A linear closure is simple and efficient to perform [14]. As a result, it is often used when the wound geometry will allow for it [14]. If a linear laceration is made in the skin, the in vivo pre-stress will result in a fusiform wound. The closure of a fusiform wound can be seen in Figure 2.2.
Figure 2.1: Examples of different types of flap geometries [13].

Figure 2.2: Fusiform wound (left) and its closure (right) [2].
2.1.2 Rhomboid flap

The rhomboid flap is one of the most commonly used surgical flaps because of its versatility and ability to close many types of wounds in many locations [13]. It can very often be employed safely and with good cosmetic outcome [13].

The rhomboid flap consists of a rhomboid, or parallelogram, wound with two incisions. It is a type of rotational flap. Although the rhomboid flap can be constructed from any internal angles preserving parallelism, the Limberg flap defines a rhomboid flap with internal angles of 60° and 120° [2, 13]. It should be noted that an ideal rhomboid flap is composed of incisions of equal lengths. Additionally, as can be seen in Figure 2.3, angles G and F’ should be equal to angles B and C, respectively.

The closure of a carcinoma resection with a rhomboid flap can be seen in Figure 2.4.

2.2 Relaxed skin tension lines

Relaxed skin tension lines (RSTLs) are imaginary lines that can be mapped to the face which correspond to the direction of stress within skin tissue [15]. RSTLs are correlated to the directionality of skin elastic...
properties and indicate the anisotropy of skin tissue properties \[15\]. RSTL distribution is influenced by histological and anatomical factors such as collagen distribution and bone structure \[15\].

![Relaxed skin tension lines drawn on patient](image1.png)

Figure 2.5: Relaxed skin tension lines drawn on patient \[15\].

RSTLs are important for any kind of facial surgery as wound closure lines that are more parallel with these lines produce less scarring and more functional results \[15\]. RSTL orientation generally correlates with wrinkle lines in aging skin, and closure lines that are parallel to RSTLs tend to be masked by the resulting wrinkle lines \[15\]. Examples of correct and incorrect wound closures can be seen in Figure 2.6.

![Z-plasty with correct and incorrect design](image2.png)

Figure 2.6: Z-plasty with a) correct design that aligns with relaxed skin tension lines and b) with incorrect design that crosses several relaxed skin tension lines (bottom) \[15\]. Note that initial incisions are indicated to the left of the arrow, and final closure lines are indicated to the right of the arrow.

As far as cosmetic outcome is concerned, scar alignment with RSTLs can be more important than scar length \[15\]. Figure 2.7 illustrates an example where a larger fusiform wound is excised around a laceration to result in a final line of closure coincident with a RSTL.
Figure 2.7: The use of a fusiform wound to align a small scar with relaxed skin tension lines [15].

2.3 Aesthetic units

Aesthetic units are regions of the face within which lines of closure should remain [2]. The concept of aesthetic units was first proposed by Gonzlez-Ulloa in 1956. It is accepted that if a scar is bounded within an aesthetic unit, it will yield better aesthetic results for the patient [17]. Conversely, if a scar extends across several units, it will have greater visibility [17]. A depiction of aesthetic units can be seen in Figure 2.8.

Figure 2.8: Aesthetic units of the a) face, b) anterior view of nasal subunits, and c) lateral view of nasal subunits [2].

Additionally, interactions between aesthetic units are possible and should be considered when selecting a method of closing a wound [17]. For example, a closure within the cheek, if resulting in enough stress, can cause deformation or sagging in skin tissue around the eye.
2.4 Facial landmarks

Facial landmarks have been used within cephalometry for many years to provide a quantitative approach to anthropometric measurements of the head and face. Recently, facial landmarks have been of particular interest in the field of computer vision for automatic face detection and pose estimation [18–22]. As a result, there have been many algorithms developed for two-dimensional image processing of the human face. Many of these techniques are now being extended for use in three-dimensional cephalometry [23, 24].

There have been many different algorithms proposed for automated facial landmark detection including ones based on geometric models, such as active appearance/orientation models [21, 24], and neural networks of various architectures [18, 19, 23, 24]. While there has been significant research into automated landmark detection for three-dimensional images [25, 26], the vast majority of research in automated landmark detection has been applied to two-dimensional datasets. This is likely because they are more commonly used than three-dimensional images, have lower dimensionality and complexity, and there exists a larger number of potential training examples.

![Example of 26 craniofacial landmarks](image)

2.5 Finite element method

The finite element method (FEM), also known as finite element analysis (FEA), is a numerical method for solving problems involving partial differential equations (PDEs) and is often applied to find solutions to problems within engineering and physics [27]. The fields in which FEM can be applied are diverse and include structural mechanics, fluid dynamics, and electromagnetics [27]. These are often problems where analytical solutions are difficult or impossible to determine [27].

FEM discretizes problems involving PDEs by subdividing the region of analysis into an arbitrary number of elements [27]. Generally, this approximate solution converges to the real solution as the number of elements increases [27]. Simplified greatly, FEM approximates a continuous solution on a set of discretized basis functions [28]. Depending on the geometry, boundary conditions, and accuracy required,
different basis functions can be employed to find a solution over \([27]\). Examples of the discretization necessary for FEM can be seen in Figure \([2.10]\).

![Figure 2.10: Discretization of a domain into a set of basis functions for a one-dimensional displacement function (left) and a three-dimensional stress analysis of a wheel (right) \([28]\).](image)

FEM was first developed in the 1940s by several independent researchers for use in solving structural engineering problems, however due to the large number of computations involved, the widespread use of FEM as an analysis tool did not become feasible until digital computing power became more powerful and accessible \([27]\). It was not until 1976, that FEA was applied to large displacement, nonlinear problems \([27]\).

FEM possesses several advantages in comparison with analytical methods including the ability to easily model complex geometries, implement different kinds of boundary conditions, and analyze nonlinear materials and large deformations \([27]\).

### 2.6 St. Venant’s Principle

In 1855, Barr de Saint-Venant proposed the following:

> If the forces acting on a small portion of the surface of an elastic body are replaced by another statically equivalent system of forces acting on the same portion of the surface, this redistribution of loading produces substantial changes in the stresses locally but has a negligible effect on the stresses at distances which are large in comparison with the linear dimensions of the surface on which the forces are changed \([29]\).

St. Venant’s Principle, was proven for nonlinear materials by Horgan and Payne \([30]\). This principle is important in approximating the far-field stress conditions of materials.

### 2.7 Skin tissue modelling and mechanics

Evidently one of the most difficult aspects of simulating plastic surgery procedures is the accurate simulation of skin properties. Due to the highly non-linear, anisometric nature of skin tissue, a closed-
form solution to deformation is extremely difficult to find in a pragmatic manner. FEA allows for the calculation of resulting strain and stress in the region as well as deformation without the difficulties of such an approach.

Significant approximations have previously been employed by other research groups in an attempt to simulate such processes. It has only been recently with work done by Flynn et al. that a more rigorous approach to the complex behaviour of skin tissue property has been undertaken \[31,32\]. Recent sets of measurements have been performed using three-axis force sensing robots to more accurately characterize the stress-strain response of human facial skin tissue \[31\]. This data was used to form a Mooney-Revlon model of the constitutive properties of skin tissue and subsequently a model of the human face \[33\].

Several researchers have employed finite element analysis (FEA) to skin tissue modelling \[34\]. The face is a particular region of interest due to the varying topology and skin tissue parameters, which have traditionally made it a difficult region to perform surgery on, as well as the highly visible nature of the face and the importance of associated aesthetics. Skin tissue is an inherently non-linear material, which also adds to the complexity of modelling its behaviour.

It should be noted that skin tissues mechanical behaviour is a direct result of its histology. Due to the composite nature of skin, consisting of collagen, elastin, and muscle, at a macroscopic level with large-scale deformations, skin tissue exhibits both non-linear and anisotropic behaviour \[35\]. However, research has suggested that this non-linear elastic behaviour can be approximated as a piecewise linear model \[35\].

In summation, one of the most crucial aspects of simulating plastic surgery is the accurate simulation of skin properties. Due to the highly non-linear, anisometric nature of skin tissue, massive approximations have previously been employed in other attempts at simulating such processes. However, recent skin property measurement data as well as computational advancements have opened the door to more accurate simulation.

2.8 Plastic surgery simulation

In 1992, Pieper, Rosen, and Zeltzer first reported the development of a computer-aided plastic surgery (CAPS) tool that applied the finite element method to three-dimensional patient data to allow for visualization of rudimentary closures \[36,37\]. While this paper pioneered the field of computer simulation as applied to plastic surgery, patient models were crude and low-resolution, and skin property models were taken to be simply linear elastic and not based on patient data \[37\]. Much of this rudimentary behaviour was due to inferior computational power and techniques at the time of publication.

A FEM approach to craniofacial surgery was proposed by Koch, Gross, Carls, et al., but the underlying skin properties were still simulated based on a linear stiffness model \[38,39\]. While this approach was an improvement upon Pieper, Laub, and Rosen, in that a more complex mass-spring system was proposed, the nonlinear, anisometric properties of skin tissue were not modelled by this system \[38\].

Most recently, research by Mitchell, Cutting, King, et al. have attempted to take advantage of the improvements in both computer hardware and finite element analysis (FEA) computational techniques, including virtual node usage in a regular lattice, to provide an improved plastic surgery simulation interface \[40,41\]. While a real-time simulation was produced, physical accuracy was sacrificed for the sake of computational speed. The developed method was intended for real-time surgical simulation and used a generic patient model with simulated physics determined by a mass-spring system \[40\]. While
the authors had stated an intention to develop a patient-specific model, this had not yet been completed.

2.9 Automated lesion segmentation

Segmentation of medical images is the process of classifying different regions of the image based on a desired set of properties, which can include anatomical structure. Automated segmentation is a prominent area of research in medical computer vision as it is a difficult problem with various applications. Of particular interest to this project is automated segmentation of dermal lesions. There has been a significant amount of research in the area of dermatological applications for lesion segmentation.

In 2009, Celebi, Iyatomi, Schaefer, et al. performed a systematic review of lesion border detection in dermoscopy images, including region-based, clustering, active contours, thresholding, soft computing, morphological, and model-based methods. Several algorithms for automated detection were compared, but due to the difficulty in defining a ground truth as well as the lack of a public dermoscopy image set for validation, it was difficult to form meaningful conclusions. Another comparison study published the same year implemented and tested four different algorithms on the same test data, and found that adaptive snakes and expectation-maximization techniques produced the best results. Other studies have had similar difficulties in quantifying the success and potential clinical benefits of automated segmentation for dermoscopy in all but the most obvious of melanoma cases.

Craniofacial landmark registration

There has also been a significant amount of research in the field of facial landmark detection. In some sense, this is also an image segmentation, or classification, problem.

Sukno, Waddington, and Whelan performed a comparative study on six different three-dimensional local descriptors in the use of correctly identifying 26 different craniofacial landmarks. No single descriptor performed significantly better than the others at correctly localizing the landmarks, although most of the detected landmarks had position errors of under 2 mm. It should be noted that this research was performed on three-dimensional medical images. Although there has been much research performed on two-dimensional facial landmark registration for pose detection and face detection in the wild, there is little for medical anthropometric facial landmarking.

2.9.1 Non-rigid registration

Image registration involves the alignment of two different images based on a set of specified features onto a shared coordinate system. Rigid registration differs from non-rigid registration in that only affine transformations are permitted. In terms of a point cloud, rigid registrations preserve relative distances between points. Non-rigid registration allows for more arbitrary and non-linear transformations to occur.

There has been quite a precedent for the application of non-rigid registration to medical images. Much research has been done on both two-dimensional and three-dimensional medical images from multiple modalities. It is proposed that non-rigid registration will be used to provide patient-specific simulation by fitting template models to patient image data.
Chapter 3

Methods

The aim of this tool is to develop a patient-specific approach to surgical planning for facial reconstructive procedures. To produce a tool that was robust in both function and application, several methods were used to provide ease of use as well as accuracy in results.

3.1 Commercial software

3.1.1 Matlab

The majority of the algorithm processing was developed using Matlab R2016b. The use of Matlab allowed for an easy-to-use framework for image processing, GUI development, access to peripherals such as the webcam, and general computations. Matlab allowed for rapid deployment of ideas as the intricacies of low-level software development could be abstracted.

3.1.2 COMSOL Multiphysics

Finite element analysis was completed using COMSOL Multiphysics. While the developed algorithm does not depend on any one specific FEA software suite, COMSOL Multiphysics was chosen for its extensive Matlab interface. This allowed the entire FEA solution to be initiated and controlled by Matlab. Results from the COMSOL solver could be easily integrated within the user interface developed with Matlab’s GUIDE framework.

3.1.3 SolidWorks

SolidWorks 2016 was used to perform some processing of the patient face template geometry to facilitate FEA.

3.2 Graphical user interface (GUI)

A graphical user interface (GUI) was developed to allow for easy use of the tool by the user. The Matlab GUIDE system was used to develop this GUI, and development was guided by several design criteria:

- Interface and interactive elements, such as buttons, must be easy to use and understand.
• Interface should require minimal interaction from user to obtain desired results.

• Results must be easily understood and interpreted by user.

• Interface should be somewhat aesthetically pleasing.

It was important that the GUI be developed for modern computing interfaces, and this included touchscreen devices. As a result, GUI elements of appropriate sizes were chosen to allow for direct touchscreen interaction. This was chosen to be as unobtrusive as possible to a clinician’s workflow, allowing for flexibility in use cases. While the tool was developed on a laptop computer, it is envisioned that a clinically useful version of this tool would be run on a mobile device such as a tablet computer.

3.3 Patient image data

Multiple modalities of patient data were considered for use as inputs to this tool. While three-dimensional optical, radiographic, and MRI data were considered for use with this tool, it was decided that two-dimensional optical images would be used. This decision was made to ensure that the tool would be easy to use with commonly available computing hardware. Two-dimensional optical cameras are ubiquitous and prevalent in most mobile devices. Additionally, a minimal number of dimensions facilitated development of the tool and subsequent image processing. The state of computer vision and image processing tools for two-dimensional data is highly mature as a research field. Thus two-dimensional images allow for a greater set of tools for image processing. Higher dimensional patient data will be explored in future work.

3.4 Lesion segmentation

A gradient vector flow (GVF), or snake, algorithm proposed by Erkol, Moss, Stanley, et al. was employed to perform lesion segmentation [51]. This approach was taken as it was tested specifically to work with dermoscopy images of lesions [51]. Generally, GVF employs an energy-based cost function that is to be minimized.

$$E_{snake} = \int_0^1 [E_{internal}(v(s)) + E_{image}(v(s))] ds$$

where $s \in [0, 1]$ and $v(s) = (x(), y(s))$ [51].

To provide optimal results, the tool employs a semi-automated approach to lesion segmentation. The user is prompted to select the centroid of the lesion to be segmented, which provides a seed point for the GVF algorithm. The user will also be able to modify the "elasticity" or energy function parameters of the GVF algorithm to ensure optimal results.

In lesion segmentation, particularly in melanoma applications, one difficult area to determine for surgical applications is resection margins. Thus this user-defined approach to segmentation is very important to allow surgeons the utmost of control in intervention. Additionally, a manual alternative will be introduced to allow for optimal lesion segmentation in the event that complete control is required by the user.
3.5 Automated facial landmark detection

To facilitate patient-specific tissue simulation and thus surgical planning, the identification of unique anthropometric landmarks is necessary. These anthropometric landmarks are well-defined and commonly used in cephalometry [24]. An example of these landmarks can be seen in Figure 2.9.

The function of these anthropometric landmarks will be manifold as they will be used to map relaxed skin tension lines (RSTLs) and also as reference for appropriate skull and soft tissue model dimensions for later stress and strain analysis.

It was decided that the neural network model by Zhang, Luo, Loy, et al. would be used [19]. This algorithm offered robust landmark detection under differing poses and lighting conditions with minimal manual segmentation or processing. Zhang, Luo, Loy, et al. employed a multi-task, deep convolutional neural network approach to automated landmark detection.

Zhang, Luo, Loy, et al.’s method consisted of a task-constrained multi-task learning (MTL) approach. The primary task to be learned was accurately identifying facial landmark, while secondary tasks included identifying pose, gender, presence of glasses, and whether the subject was smiling [19]. These tasks were optimized according to the following objective function

\[
\arg\min_{W^r, (W^a)_{a \in A}} \sum_{i=1}^{N} \ell^r(y^r_i, f(x^r_i; W^r)) + \sum_{i=1}^{N} \sum_{a \in A} \lambda^a \ell^a(y^a_i, f(x^r_i; W^a))
\]

where \( r \) denotes the main task, \( A \) denotes the set of secondary tasks, \( x \) is the feature vector, \( y \) is the label, \( \ell \) is the loss function, \( W \) is the set of weights to be trained, and \( \lambda \) is the ”importance” weight of the given secondary task.

Task-wise early stopping of training allowed the avoidance of local minima and allowed training of the primary task to be prioritized over the secondary tasks [19]. The convolutional neural network (CNN) structure can be seen in Figure 3.1.

![Figure 3.1: Tasks-constrained deep convolutional neural network architecture for automatically detecting facial landmarks](image)

Manual landmark registration

As a redundancy, manual craniofacial landmark assignment was also afforded to the user in the event that the automated system ever failed. A simple point-and-click interface was used to select various landmarks in sequence.
3.6 Relaxed skin tension line (RSTL) mapping

To map RSTLs to the image of the patient’s face, a template image of face RSTL orientations was warped to match the patient’s face based on the estimated facial landmark algorithm. This was achieved by registering and warping corresponding landmarks on the template image to landmarks on the patient images. It should be noted that while the patient image landmarks were determined by the automated landmark detection algorithm, the template image was manually landmarked. These positions of these landmarks were saved for repeated use.

![Template of relaxed skin tension lines to be fit to patient image](image)

Both the template and patient images were meshed using a Delaunay triangulation algorithm on the corresponding facial landmarks. Each of the resulting triangular regions of the template image were then warped to the corresponding triangular region of the patient image by a simple projective transformation

\[ \tilde{x}_{\text{patient}} = A \tilde{x}_{\text{template}} \]

where \(x\) and \(x'\) are the landmark locations in image coordinates of the patient and template images, respectively, and \(A\) is the appropriate transformation matrix.

\(A\) was solved for by finding \(\tilde{x}_{\text{patient}} \tilde{x}_{\text{template}}^{-1}\) and then subsequently used to warp each triangular region of the template image. This template image was then overlaid onto the patient image. This algorithm is illustrated in Figure 3.3.

3.7 Finite element analysis (FEA)

To simulate the closure of the surgical flap geometries, a finite element analysis (FEA) approach was taken to simulate skin tissue mechanical properties. Again, this approach was taken due to the complexities of modelling skin tissue including nonlinear material properties, complex geometries, and large deformations.
3.7.1 Overview

In order to reduce initial complexity of the project and ensure accurate modelling, it was decided that the project would be divided into several intermediate models:

1. A given surgical flap geometry for a two-dimensional, square region of linear elastic tissue.
2. A given surgical flap geometry for a two-dimensional, square region of nonlinear, hyperelastic tissue.
3. A given surgical flap geometry for a three-dimensional, block of nonlinear, hyperelastic tissue.
4. A given surgical flap geometry for a three-dimensional, human face geometry of nonlinear, hyperelastic tissue.
5. Iterate previous model with different proposed constitutive models for skin tissue.

This staggered approach allowed for comparison of results with previous research that had modelled skin in lower dimensions and in square tissue regions [14, 52, 53].

3.7.2 Surgical flap geometry

Two closure geometries were selected for analysis: the linear/fusiform closure and the rhomboid flap. Both geometries were selected due to their ubiquity in clinical use. The fusiform wound was chosen due
to its simplicity of modelling to act as a proof-of-concept.

The fusiform and rhomboid flap wound geometries were modelled as CAD parts. Both of these geometries were modelled as two-dimensional, plane geometries. These geometries were then extruded into a three-dimensional geometry representing either a square piece of tissue or a patient’s face. These geometries can be seen in Figure 3.4.

![Figure 3.4: CAD representations of a fusiform wound (left) and rhomboid flap (right).](image)

The fusiform wound was taken to be defined as the intersection of two partially overlapping circles, and the rhomboid flap design was designed according to dimensions defined by Weerda [2].

While only specific wound geometries were selected for the purposes of this project, this tool has been designed to allow for the composition and simulation of any surgical flap geometry. This can be achieved with any geometry that can be defined by a polygon defined by specific coordinate points and the corresponding lines of closure.

### 3.7.3 Patient face geometry

To allow for generality in modelling, the wound geometries were developed separately from the target, or patient, geometries. This allowed for any combination of the two to be easily used without significant modification to the tool workflow.

A CAD file based on a 3D camera image of a male face was used as a patient template [54]. This geometry was selected for its high resolution and open licensing. This geometry can be seen in Figure 3.5. This geometry was modified to segment just the layer of skin.

### 3.7.4 Patient-specific, non-rigid registration

It is proposed that a two-dimensional image with annotated facial landmarks be used as a template to which a pre-fabricated three-dimensional mesh of a face will be non-rigidly registered to. This allows any two-dimensional optical patient image to be used to develop a finite element analysis. Due to the wide availability and low-cost of such optical cameras, this will greatly simplify the platform of this project. Additionally, this also reduces the complexity in generating an accurate mesh of a patients face and then having to process it for analysis. It should be noted that surface scanning could provide more accurate patient specifications and data and may be explored at a later date. An image of the pre-fabricated face mesh can be seen in Figure 3.5.
3.7.5 Geometry assembly

In order to form the final geometry for the FEA modelling, the appropriate wound geometry was added to the non-rigidly registered patient face geometry through an extrude cut operation, i.e. the two-dimensional wound geometry was projected onto the patient face geometry at the appropriate location, and the difference of the patient face geometry and the extruded wound geometry was taken. The resultant geometry of the process can be seen in Figure 3.6.

Figure 3.5: Three-dimensional mesh to be used as template for FEA [54].

Figure 3.6: Fusiform wound left and rhomboid flap (right) geometries added to patient face geometry.
3.7.6 Meshing

After the geometry to be studied was finalized, it was required that the geometry be meshed for FEA study. It was important that an appropriate mesh was generated as this can significantly affect the results of the method.

COMSOL’s built-in meshing algorithm was used to mesh the patient geometry. Due to the complex nature of the simulation, appropriate meshing became very important for accurate analysis.

Some problems that were inherent to this project included:

- Large deformation
- Nonlinear, hyperelastic material
- Complex facial feature geometries
- Angular wound geometries under large stresses

As a result of these complexities, certain approaches were taken while meshing. An adaptive meshing approach was used to remesh the patient geometry multiple times to provide increased accuracy and granularity at points of high stress. Defeaturing was used around sharp corners of the wound geometry to prevent stress singularities from occurring. Additionally it was assumed that points far enough away from the wound closure were considered to be unaffected by the stress induced by the wound closure according to St. Venant’s Principle.

A mesh refinement study was performed to ensure that features were properly meshed. It is important to note that certain trade-offs were necessary to ensure both convergence of the study as well as acceptable results. As the nature of this tool did not necessarily require absolutely accurate results so much as relatively accurate displacement, certain corners were literally cut to ensure fast processing time on the equipment being used.

3.7.7 Skin tissue constitutive model

Skin is often modelled as a hyperelastic material with model parameters based on experimental data. A significant body of research has grown in the analysis of skin mechanical properties. Several constitutive models have been presented to account for skin mechanical behaviour. This tool was developed to allow for the use of any one of these models depending on the preference of the user and the patient.

It should be noted that the skin properties of different patient populations and demographics can vary significantly [55–61]. While there have been several normative studies of skin properties, this tool will allow for the customization of skin tissue properties by the user based on age and other demographics. For example, skin elasticity decreases with age [55, 62], and material parameters can be tweaked for these variances.

For the sake of testing this tool, several linear and hyperelastic models were used to model skin properties. These included Mooney-Rivlin and Yeoh models as based on various papers [31, 41, 52].

The selection of the appropriate skin model is left to the user. However, a two parameter Mooney-Rivlin model by Flynn, Stavness, Lloyd, et al. was selected as the default option.
Plasticity

Although defeaturing, or filleting, was used for sharp corners in the geometry, large deformations often still resulted in very sharp elements within the mesh. As a result, this produced singularities of very high stress. The reason for this can be intuitively reasoned by recognizing that pressure approaches infinity as the area over which the force is applied approaches zero. Although these singularities could be ignored at further distances based on St. Venant's Principle, these areas of high stress concentration actually posed problems for the solver to reach a converged solution. As a result, an elastoplastic model was introduced. This model was set to behave in a perfectly plastic fashion when stresses over 1 GPa occurred.

3.7.8 Dermal layers

The patient face template geometry was segmented into three layers to represent the epidermis, dermis, and subcutaneous layers. Different constitutive models can be conferred to each of these regions.

3.7.9 Aesthetic regional units

Different aesthetic regional units possess different material properties. For example, the skin over the eye generally possesses much more compliance than other tissue. It is obvious that a wound closure should minimize the amount of deformation and strain in other aesthetic regional units. The difference in elastic properties of the aesthetic regional units can be modelled with different constitutive models. Thus the patient face model has been composed of several domains to allow for the conference of these different material properties. This can be seen in Figure 3.7.

![Figure 3.7: Domain partitioning of patient face template geometry for varying elastic properties with elliptical wound (red).](image-url)
3.7.10 Fixed constraints

The edge boundaries on the perimeter of the face mesh were assumed to be fixed. This assumption was based on St. Venant’s Principle, assuming that the outer boundaries of the face were distant enough from the wound to allow stress effects from wound closure to be negligible. Additionally, the corners of the eyes were also fixed based to maintain anatomical accuracy. The rear side of the patient face mesh was assumed to behave under roller conditions, since skull and soft tissue structure were assumed to be significantly stiffer than skin tissue.

3.7.11 Wound closure

Wound closure was achieved through several modelling steps. Prescribed displacements were used to close the edges of the wound based on the flap geometry. For example, in the fusiform wound, the edges of the wound were given a defined displacement of the midline of the wound. Due to the large deformation, prescribed displacements were ramped in a parametric fashion to facilitate convergence of the solver. After the wound was closed, an ideal adhesive was used to bond the appropriate boundaries of the closed wound, where decohesion was not assumed to be possible. The resulting displacements were then taken to be the final lines of wound closure.

3.7.12 Accuracy vs. Computation time

Depending on the application of the tool and the desired speed of computation time, the tool was designed to allow for variable accuracy. This included varying the mesh element sizes, with coarser meshes producing faster calculation times with less accuracy. The nonlinear behaviour of the material was also parameterized so as to allow for better convergence if a solution was difficult to find for a particular hyperelastic model.

3.8 Visualization & User verification

The GUI will allow for user verification after all calculations and morphing have been completed. Various aspects of the algorithm and its results may be tweaked to suit the needs of the particular procedure and patient. For example, incision and closure placement can be adjusted as well as flap geometry.

Final wound closure lines based on displacements determined by the FEA solution will be plotted on the original patient image. The user can then use these plotted closure lines to determine whether the wound placement and geometry is an appropriate treatment for the given patient. If this is not the case, any aspect of the process can be modified and reiterated.
Chapter 4

Results

4.1 Graphical user interface (GUI)

4.1.1 Patient image acquisition

The GUI first presents the user with an interface for taking their picture via webcam. While the internal webcam of the device, in this case a PC laptop was used, any image acquisition device can be used. A simple two-dimensional optical image is acquired. Visual reference guides in the form of red rule lines are overlaid on the preview image to facilitate automatic landmark registration.

A prompt for patient image data was included in the GUI. An option to obtain the patient image via optical camera was included as well as the ability to import an existing patient image. This can be seen in Figure 4.1

![Figure 4.1: GUI: Patient image acquisition.](image-url)
4.1.2 Relaxed skin tension line estimation

After the image is acquired, the relaxed skin tension lines are plotted on the image for review. This can be seen in Figure 4.2. If the estimated RSTLs are unacceptable to the user, the patient image can be reacquired.

![Figure 4.2: GUI: Relaxed skin tension line display.](image)

4.1.3 Wound geometry selection

Once the RSTLs have been plotted, they can be used as an aid by the user to orient the selected wound geometry. The user can tap on the image to place the wound geometry. The user can then use the slider controls to the right of the image to modify geometry properties. The user is able to rotate and scale the geometry, modify internal angles, and view the approximate lines of closure of the wound. This process can be seen for a fusiform wound in Figure 4.3 and for a rhomboid flap in Figure 4.4.
Figure 4.3: GUI: Wound geometry selection for a fusiform closure: initial wound placement (top), rotation and scaling of wound (middle), and approximate lines of closure (bottom).
Chapter 4. Results

4.1.4 Visualization & User verification

After the final wound geometry is selected by the user, the appropriate CAD geometry is generated, and an FEA solution is computed by the COMSOL solver. The results of this solver, once available, are overlaid on the original patient image. These results can be seen in Figure 4.5. These results can be reviewed by the user and the wound geometry can be modified if more satisfactory results are required.
4.2 Automated facial landmark detection

Results of the landmark detection algorithm can be seen in Figure 4.6. The algorithm performed very well under various poses, different lighting conditions, and despite occlusion by glasses or hair.

Figure 4.6: Automated facial landmark detection results using Zhang, Luo, Loy, et al.’s method [19].

4.3 Relaxed skin tension line estimation

The relaxed skin tension line (RSTL) estimation results can be seen in Figure 4.7.
4.4 Finite element analysis (FEA)

4.4.1 Fusiform wound closure in square tissue region

Modelling of the fusiform wound closure in a square tissue region represented the most simple of simulated closures. The meshes used for modelling can be seen in Figure 4.8. Several different constitutive models were tested.

The results of the simulated von Mises stress can be seen in Figure 4.9.
Figure 4.9: Von mises stress in a fusiform wound closure in a square region of tissue. The white line indicates the final line of closure.

The results of the simulated displacement in the z-direction (out of plane) can be seen in Figure 4.10. Note that these results are representative of puckering of the skin tissue.

Figure 4.10: Displacement in z-direction (out of plane) in a fusiform wound closure in a square region of tissue.
4.4.2 Rhomboid flap closure in square tissue region

Modelling of the rhomboid flap closure in a square tissue region represented a more complex closure due to larger deformations and asymmetry of the geometry. The meshes used for modelling can be seen in Figure 4.11. Several different constitutive models were tested.

Figure 4.11: Meshes used to generate an FEA solution for rhomboid flap closure: initial mesh (left), mesh after adaptive refinement (right).

The results of the simulated von Mises stress can be seen in Figure 4.12.

Figure 4.12: Von mises stress in a rhomboid flop closure in a square region of tissue. The while line indicates the final line of closure.

The results of the simulated displacement in the z-direction (out of plane) can be seen in Figure 4.13.
Note that these results are representative of puckering of the skin tissue.

![Figure 4.13: Displacement in z-direction (out of page) in a rhomboid flap closure in a square region of tissue.](image)

4.4.3 Fusiform wound closure in human face

Modelling of the fusiform wound closure in a full human face geometry represented the most simple of simulated closures for the face geometry. The results can be seen in Figure 4.14. Several different constitutive models were tested.
4.4.4 Rhomboid flap closure in human face

Modelling of the rhomboid flap closure in a full human face geometry can be seen in Figure 4.15. Several different constitutive models were tested.
Figure 4.15: Von mises stress in a rhomboid flap closure in a full human face geometry. The while line indicates the final line of closure.
Chapter 5

Discussion

5.1 Results of automated facial landmark detection

The landmark detection results in Figure 4.6 are consistent with results produced by Zhang, Luo, Loy, et al.

5.2 Relaxed skin tension line estimation

From Figure 4.7, it can be seen that the relaxed skin tension line (RSTL) results appear to be consistent with those produced by experts such as can be seen in Figure 2.5. The estimated RSTLs did present some distortion around the edges of the projection in poses deviating from head-on view. This distortion could be improved by introducing a higher resolution of triangulation and thus landmarks. However, for the purposes of this project, it can be assumed that patient images can be taken so as to ensure the patient’s face is directly facing the camera.

5.3 Results of FEA of surgical flaps

5.3.1 Linear closure

Capek, Jacquet, Dzan, et al. employed a viscoelastic constitutive model for their simulation of the closure of an elliptical wound [63]. Their steady state results compare nicely with the results of this developed model being in the same order of magnitude despite using a different constitutive model.

Yoshida, Tsutsumi, Mizunuma, et al. also conducted a similar study with a focus on skin displacement after closing [64]. Their results compare nicely with the results of this developed model including the characteristic puckering at the edges of the closure.

5.3.2 Rhomboid flap

Topp, Lovald, Khraishi, et al. studied the closure of a rhomboid flap in a square tissue region. Although Topp, Lovald, Khraishi, et al. used a Yeoh constitutive model, their results compare quite similarly with the results of the developed software tool with high points of stress in corresponding regions as well as stresses in the same order of magnitude.
5.4 Future work

5.4.1 Validation

A study has been proposed to further validate this software as a surgical educational tool by testing its use with plastic surgery residents. The following experimental setup is proposed:

1. Plastic surgery residents will be presented with an image of a patient’s face and the given pathology to be resected.

2. The resident will be told what surgical flap geometry should be used to close the resulting wound. The resident will be asked to draw the necessary incision lines on the patient image.

3. The resident will be asked to draw where the resulting lines of closure will lie on the patient image.

4. The resident will perform a different wound closure of similar difficulty with the aid of the developed software tool. The surgical flap designs of each method will be assessed and graded by an expert.

This aim of this study is to investigate whether any significant statistical differences exist in performance between the two methods.

Furthermore, although this software tool employed several validated skin tissue constitutive models, results of the tool should be validated experimentally with a cadaveric model or patient model for verification. Several surgical flap geometries will be implemented on a cadaveric head, and the resultant skin displacements will be compared with those predicted by the tool.

5.4.2 Flap geometries

The goal of this project was to develop a software tool that could act as a modelling platform for any type of wound closure. As a result, other flap geometries could easily be studied as long as they are representable within a CAD geometry format. Surgical flaps such as the z-plasty and advancement flap would be obvious choices to investigate next due to their common clinical use.

5.4.3 Portability

To ensure that the device can be used in a clinical setting, with relative ease, it would be helpful for the tool to be ported to a mobile first environment such as iOS or Android. This would allow surgeons to use more portable devices to minimize impact on surgical workflow.

In order to port the tool to different platforms, a shift away from commercial software would be necessary. Several open source FEA libraries exist including deal.II. The feasibility of porting these libraries to other platforms should be investigated.

5.4.4 Wound interaction with aesthetic regional units

Further study and refinement of the developed method is necessary to more accurately represent the interactions between different aesthetic regional units.
5.4.5 Image morphing

Once FEA has completed, it is important to be able to visualize the results in a manner that is clinically relevant and easily understood by the user. Calculated tissue displacements will be used to perform image morphing on the original input patient image in order to visually display the results of the closure to the user. This visualization will also afford better communication regarding potential patient outcome. Several standard image morphing transformations will be employed, including basic linear algebra transformations, e.g. affine. This image morphing will be done in a manner very similar to the initial RSTL mapping. Additionally, further refining of the mesh will be necessary around regions of interest and high displacement. A standard Delaunay triangulation method will be used for this approach initially.

5.4.6 User interface

Further refinements to the user interface will be required to make the system more viable for any sort of commercial product. More advanced settings should be made available to the user but not at the cost of simplicity in use. Further investigations into the User eXperience (UX) design will be necessary.

5.4.7 Relaxed skin tension line field

Currently the relaxed skin tension lines (RSTLs) are generated in the form of a discrete bitmap. While this is suitable for human perception and use, a more continuous approach will be necessary to aid further use of RSTLs in simulating skin mechanics. For example, the anisotropic nature of skin was not considered within the scope of this project. In order to account for this, it is proposed that a vector field representation of RSTLs be developed. This would greatly aid in further accuracy of this tool.

5.4.8 GUI for design of arbitrary CAD flap geometry

While any flap geometry can be simulated by the developed tool, it is not intuitive for a user without knowledge of at least two-dimensional CAD to implement any unique geometries. It is proposed that an intuitive graphical user interface (GUI) be developed for such a user to have greater control over possible treatments.

5.4.9 Patient image modalities

Other patient image modalities should be explored so as to offer a greater level of accuracy in simulated geometry. Three-dimensional data such as three-dimensional optical cameras, surface computed tomography, and surface MRI data should be explored. With this shift to a higher dimensional image space, a robust way of detecting landmarks in three dimensions will also need to be explored [26].

5.4.10 Extension to other regions

While this project has focused on the face due to the very high visibility of the region, this tool could be extended for use anywhere on the body that requires a patient outcome with minimal scarring.
5.5 Significance

This project has the potential to greatly improve surgical education. While this software tool is not intended to act as a replacement for hands-on training that is the cornerstone of traditional surgical education, it could greatly facilitate visualization of flap geometries for a field that is difficult to understand.

Additionally, this software tool, if further validated can help to act as a predictive and optimization tool within the clinical environment. It would not only be able to simulate the results of a defined flap geometry and closure but also act as a tool to optimize input geometries to ensure further decreases in stresses contributing to hypertrophic scarring as well as displacement of surrounding aesthetic regional units.

Finally, this work could lay the foundation for fully automated procedures. While the developed software tool is far from a robotic control system, the computer vision components and mapping of incision lines to closure lines will be crucial to any future automated system.
Chapter 6

Conclusion

In conclusion, a tool was developed that allowed for automated facial landmark detection, relaxed skin tension line estimation and plotting, CAD geometry generation of a face with arbitrary wound geometry and placement, and simulation of wound closure with derived strains, stresses, and displacements.

It is the author’s hope that this tool experiences continued development. While this is very much a foundational project, the potential for clinical benefit is significant.
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