FIXING THE FACE AND ITS FOUNDATION:
A NOVEL TREATMENT PLANNING WORKFLOW FOR CRANIOMAXILLOFACIAL SOFT TISSUE AND SKELETAL RECONSTRUCTION

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Purpose: The craniomaxillofacial (CMF) skeleton and its associated soft tissues form a complex 3D structure important to function (i.e. sight, speech, chewing, and sense of smell) and an individual’s self-perception (physical appearance). Facial anatomy can be impacted by trauma (i.e. car accidents, sporting and military injuries) or pathology (i.e. cancer or congenital disease). After a traumatic injury or pathologic change to the face, an individual’s primary desire is to return to their original state both in terms of function and their appearance. However, there is generally insufficient information regarding the shape of an individual’s pre-injury/pathology face and the underlying bone. This makes accurate restoration of appearance through surgery extremely challenging, with much of the work of a plastic surgeon dependent on their experience and 3D spatial visualization abilities. Current computer-assisted methods are especially ineffective in bilateral cases, where mirroring the face or skull’s available geometry is not possible, and for nasal defects, where the nose is on the medial mirror plane.

In society today, we do however, have an increasing number of photographs of ourselves, especially since advent of mobile digital cameras and social media sites. Technological innovation in the field of computer vision has recently enabled the generation of 3D models from 2D pictures, but a high accuracy of these models is required to guide surgical facial reconstruction. This project has developed a workflow to guide surgical reconstruction of the face by integrating and optimizing 2D to 3D technologies (in computer vision and manufacturing) that take advantage of pre-injury/pathology photos and the relationship between our appearance and the underlying bone structure. It was hypothesized that existing non-clinical computational algorithms used in computer vision, forensics and manufacturing can form the foundation for a clinically relevant workflow to facilitate treatment planning for surgical reconstruction and improved accuracy of severe craniomaxillofacial soft tissue and skeletal injury/pathology.

Methods & Results: This work developed a surgical planning workflow that applies existing and optimized image processing and computer vision techniques to estimate a patient-specific 3D face model that can be used for translating shapes into intra-operative guides for CMF reconstruction. Accurate restoration of premorbid appearance is extremely challenging when based solely on 2D photos, often provided to a plastic surgeon for visual reference of a patient’s pre-injury/pathology face. However, a 3D face model can be determined from a 2D photograph using algorithms including facial detection (finding faces in images), recognition (identifying a specific face in a group), landmark determination (locating points of interest on a face), and most importantly, 3D morphing (3D landmark-based shape estimation using a trained database). With a patient-specific 3D face model, forensics data can provide a relationship between the skin and the bone to estimate the 3D skull morphology. The calculated face and skull morphologies can then be used to manufacture 2D and 3D templates to translate digital planning to the intraoperative physical space. With the requirement for high and well characterized accuracy in restoring the human CMF anatomy, validation of such algorithms is critical to quantify expected errors in different facial regions and account for varying face shapes which may be influenced by age, sex, ethnicity and BMI. The image processing and pre-operative planning workflow for the proposed craniomaxillofacial (CMF) reconstruction pipeline is outlined in Figure 1. The research undertaken has been to develop, validate and test each process step of this workflow.

Quantification of clinically relevant accuracy of 3D face morphable models generated from pre-injury/pathology photographs. Using an existing pipeline, 3D face shapes can be generated by fitting automatically landmarked 2D photographs to 3D morphable face models (e.g. the Basel Face Model, BFM). To validate the ability of this pipeline to yield sufficient accuracy for CMF surgical planning, 4 morphable models were evaluated and the BFM ultimately applied to 100 subjects in the Binghamton University facial expression (BU-3DFE) database. The 3D model output (geometry) was compared to 3D face scans of the same individuals generated using stereo-photogrammetry. Model performance considered the morphable face model used, photos required (number and pose), and participant specific
parameters (i.e. age, sex, ethnicity and BMI). Morphable model accuracy was evaluated by comparing surface distances (per-vertex Euclidean distance) to the rigidly registered (iterative closest point) 3D scan. Distance errors <2.5 mm were deemed acceptable target values, comparable to manual surgical planning and manipulation.

The regional accuracy analysis quantified the performance of the morphable models; in particular, the BFM 2017 morphable model yielded estimates in the areas of the eye, cheek, chin, forehead and mouth regions that had an acceptable clinical error for all subjects. However, significant differences were found for the average RMS nose distance error when controlling for race (Caucasians: 2.4 mm, East-Asian: 4.8 mm) and sex (Male: 2.5 mm, Female: 3.6 mm). The Caucasian male nose was the only category of subjects whose 3D nose shapes were estimated with a clinically acceptable error using the BFM 2017 morphable model. The average RMS and maximum distance errors specific to the facial regions of interest, as well as the patient’s sex and race, are important considerations in utilizing these models to guide CMF reconstruction when no other 3D shape information is available and motivate further work to reduce bias in such models (i.e. inclusion of more diversity in the cohorts from which they are developed).

**Development of skin templates for nasal reconstruction from 3D geometries.** Total and partial nasal reconstruction present a particularly complex soft tissue resurfacing issue (with skin flap transfer from adjacent forehead sites, distant sites, or through expansion of adjacent/regional skin). Elevation and transposition of vascularized skin from the forehead is the gold standard technique for nasal reconstruction. Currently, the skin pattern for the forehead flap is designed by reverse planning, whereby the surgeon manually folds a template to resemble a 3D nasal shape, and then unfolds the shape to generate a 2D pattern. To address this application, we extended our 2D to 3D planning pipeline to guide the creation of forehead flap templates for intraoperative nasal reconstruction and applied this pipeline to 5 clinical cases. Once a 3D model of the face was constructed (based on 2D photos or other available pre-injury/pathology imaging), the pipeline was developed to integrate fabric “patterning” software (used in the upholstery industry) to create 2D skin templates. In this, creation of clinically useful templates required consideration of the nasal aesthetic subunits. The digital templates were then translated into the physical space which provided a forehead flap intra-operative cutting template.

An example case of this novel workflow for pre-operative planning is provided in Figure 2 in which a patient with a complete bilateral rhinectomy had his 3D nose shape generated using the morphable model and a flattened complete nose template with aesthetic subunits was generated to guide the surgical reconstruction. In the case series completed (n=4 cases went to the operating room) the shape guides were utilized with labelled aesthetic subunits assisting with alignment and were qualitatively described as advantageous and time-saving.

**Inferring skull geometry from 3D facial morphology:** In forensic sciences, faces can be reconstructed from a found skull geometry utilizing a soft-tissue depth model. For example, the TD Morpheus soft tissue depth model includes the effects of age, sex and BMI on face shape and has been validated using head CT images. As such, within the developed pipeline, the generated 3D models of an individual’s pre trauma/pathology photos can be further used to determine the underlying skull shape. To determine an “inferred skull” shape from 3D facial morphology, we ‘reverse-engineered’ the forensics’ tissue depth model. This pipeline was applied to 33 segmented head CTs. Using the Euclidean distance measure as implemented by the forensics model led to inaccurate estimates of concave skeletal surfaces where the face is convex. As such we implemented a new perpendicular tissue depth measurement algorithm that was able to overcome this limitation by probing inwards along the face’s normal vectors until contacting bone (Figure 3). In applying this new soft tissue thickness mapping algorithm, spatial distribution on the skull illustrated that the upper facial bones demonstrated accurate correspondence between the forensics model and the CT-derived measurements. Specifically, performance was strong in regions with facial soft-tissues less than 10 mm thick (e.g. forehead/
frontal bone and zygomatic arches). Reconstruction of the skeletal geometry in these areas is clinically important as they represent regions where facial fractures are more likely to occur, and can be used in combination with atlas-based methods to guide skeletal geometry estimates in regions with greater soft tissue coverage.

**Measuring 3D regional facial displacement from smiling to neutral expressions.** The utilization of existing 2D photographs to generate 3D CMF reconstructions, must address the implications of facial expression, as individuals are most often smiling in pre-injury/pathology photos provided to clinicians, but are then in a neutral expression under anesthetic. A quantitative understanding of 3D facial geometry in the context of facial expression is also important in the context of addressing facial paralysis with reanimation surgery. When the facial nerves are not working, muscle paralysis (palsy) removes the ability to express emotions (e.g. smile). Reanimation surgery seeks to restore control of facial movement by transferring functioning nerves and/or facial muscles. As such, a quantitative 3D analysis of smile movement was performed to provide distance and angle measurements for a normal smile’s lip and cheek movements to generate data to better inform facial reanimation surgery (i.e. guide the length of muscle to cut and transfer). To address this need, a database of 3D face scans (BU-3DFE, n=100) was analyzed to measure smile movement in 3D over an increasing extent of smiling. Each subject’s set of 3D scans was rigidly registered to measure average displacement vectors (distance, azimuth, elevation) and a per-vertex Euclidian distance between the neutral and happy expressions. The positions of the philtral, mid upper lip, commissure, mid lower lip and lower lip midpoint were measured to track mouth movement. By comparing 3D displacement between the happy and neutral expressions, the subtle movements of the mouth and cheeks during smiling were elucidated and quantified.

**Assessing nasal symmetry using mobile 3D scanning technology.** Symmetry of the facial anatomy is an essential goal to restoring both form and function in facial reconstructive surgery. In particular, the nose is a focal point of a patient’s face and asymmetry can impact an individual’s psycho-social wellbeing and breathing. Currently, intraoperative measurement of nasal symmetry and displacement is limited to visual assessment with rulers yielding errors in the range of up to 2-3 mm. An algorithm was developed to use new mobile 3D scanning technologies (iPhoneX with FaceID using Bellus3D’s FaceApp) that enables intra-operative quantification of nasal symmetry. The technique developed automatically evaluates nasal symmetry from a 3D scan by aligning to the orthogonal planes. The asymmetry is evaluated as the maximum distance from the medial plane along the dorsum to the nose tip. The average deviation analysis was conducted on 100 subjects (BU-3DFE database) to provide context with respect to population nasal asymmetry as a baseline for the comparison of deviations measured in individual patients. This nasal deviation measurement algorithm may be used to form the basis of a new clinical assessment tool with an ultimate goal of providing pre-operative and intra-operative measurements to guide restoration of nasal symmetry.

**Conclusions:** These computer vision-based technologies are being integrated into a cohesive 2D to 3D surgical planning pipeline for traumatic CMF reconstruction. The novel approach exploits the ubiquity of face photos and combines repurposed and optimized existing non-clinical software with new algorithms and digital/physical templates to improve the ability (speed and accuracy) of surgeons to restore pre-injury/pathology CMF soft tissue and skeletal morphology. The technology developed will potentially lower costs by shortening OR time and improve cosmetic outcomes. The 3D face shapes provided by this work are being developed into translational tools and templates to help guide craniofacial reconstruction. Physical intraoperative surgical guides for skin flaps are made from modeled 3D faces and underlying bone structures using 3D printing and 2D flattening software. Ultimately these technologies will be integrated into a highly automated surgical planning pipeline to help restore form and function of pre-injury/pathology appearance in patients with severely compromised facial anatomy.
**Figures**

Figure 1: Workflow schematic of 3D face and skull shape analysis for reconstruction pre-oeprative planning.

Figure 2: A) Complete bilateral rhinectomy (front & profile view) B) Photo of patient prior to skin cancer and resection, C) Face estimated from Basel Face model (BFM) with skin texture mapping, front and side view surfaces, D) Nose defect after rhinectomy. E) Nose from BFM cropped to fit into 3D defect shape (front & side view), F) Estimated 3D nose shape isolated. G) Flattened complete nose template with aesthetic subunits (not to scale).

Figure 3: a) Segmented face isosurface from head CT, b) segmented skull isosurface from the head CT, c) segmented translucent face and underlying skull, and d) the soft-tissue distances measured along the normal direction between the face and skull, with a colormap visualized in the range from 0 to 20 mm.