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Biomechanical optimization of a custom-made positioning and fixing bone plate for Le Fort I osteotomy by finite element analysis

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ABSTRACT

This study integrates image-processing, finite element (FE) analysis, optimization and CAM techniques to develop a bone plate that can provide precise positioning and fixation for the Le Fort I osteotomy. Two FE 3D models using commercial mini-plate and continuous bone plates were generated by integrating computed tomography images and CAD system for simulations under the worst load condition. The goal driven optimization method was used to examine the system performance using certain minimum output values for relative micro-movement between the two maxillary bone segments and stress for the bone plate to seek maximum reduction volume in a continuous plate. The simulation results indicated that the maximum stress/relative micro-movement was 1269.20 MPa/133.66 μm and 418.37 MPa/92.37 μm for the commercial straight mini-plate and continuous fixation types, respectively. The optimal design plate found the volume reduction rate reach 24.3% compared to the continuous bone plate and the decreased variations in stress/relative micro-movement were 65.14% (442.36 MPa) and 29.36% (96.53 μm) when compared to values obtained from the commercial mini-plate plate. The optimal bone plate can be manufactured using a 5-axes milling machine and fixed onto the freed separate maxillary segments of a rapid prototyping model to provide precise positioning/fixation and present adequate strength/stability in the Le Fort I osteotomy.

1. Introduction

The Le Fort I osteotomy is a commonly used surgical method to correct midfacial deformities. The osteotomy concept is made with a reciprocating saw to separate the maxillary into different free segments. The desired movements are made in relation to preoperatively measured external reference points. Once the freed segments are moved into the proper position, the maxilla should be fixed with titanium mini-plates and screws to achieve mobilized segment skeletal fixation for the Le Fort I osteotomy [1]. This method is indicated often in conjunction with improving facial contour, eliminating asymmetries, and establishing good occlusion in patients with hyperplasia, hypoplasia, obstructive sleep apnea or cleft lip and palate [2–5].

Traditionally, the freed maxillary segment positioning for the Le Fort I osteotomy is based on preoperative model surgery, using articulated dental models made from plaster casts of the patient's occlusion. However, precise osteotomy execution with exact positioning and osteotomized fragments fixation is usually difficult to reproduce using only limited 2D projection images, especially in maxillary impaction or downward displacement cases [4,6,7]. Although preoperative virtual surgery planning and rapid prototyping surgical guides were applied in Le Fort I osteotomies to reproduce precise and predictable freed Le Fort I segments in three-dimensional (3D) space [6,7], commercial straight mini-plates still demand contouring to fit segmental maxillary geometry profiles for each individual patient during surgical operation. Contouring the accuracy and fit of individualized commercial straight mini-plates requires extensive advance preparation. Residual stress during repeated contouring (bending) of the straight mini-plates also increases the risk for a bone plate to suffer fatigue failure [6].

Patient specific mini-plate systems have been proposed to overcome challenges with exact positioning and mini-plate countering e.g. for the Le Fort I osteotomy [8]. However there are concerns over mechanical failure in such implants, their optimal design and manufacturing for Le Fort I osteotomy with large advancement.

This study integrates medical image-processing, finite element (FE) analysis, optimization and computer-aided manufacture (CAM) techniques to develop an optimal designed bone plate that can provide custom precise positioning and fixation under adequate strength and stability for the Le Fort I osteotomy with large advancement.

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2. Materials and methods

Fig. 1 shows an overview of this study including 3D maxillary model reconstruction, bone plate/screw system biomechanical analysis, goal driven optimization, plate manufacturing, experimental model development and validation of finite element models.

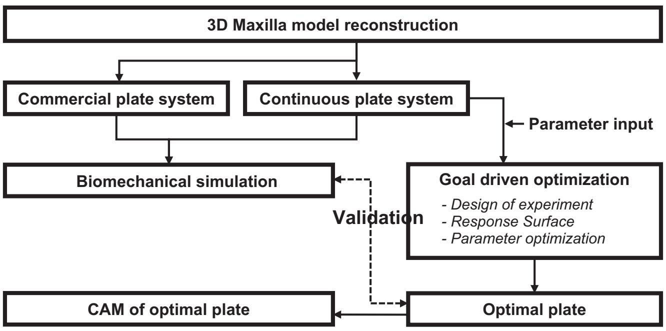

Fig. 1. Flowchart of this study.

2.1. 3D maxillary model reconstruction

The patient was a 19-year-old male patient with skeletal Class III occlusal features. The LeFort I osteotomy was designed for treatment. A CT (computed tomography) scan (i-CATTM scanner, Imaging Sciences International, Hatfield, PA) with 0.4 mm interval was performed on the patient to reconstruct the 3D maxillae model with the contours of various hard tissues (cortical and cancellous bone) identified using commercially available image-processing software (Amira, v4.1, Mercury Computer Systems, Chelmsford, MA). A 3D solid model of the maxillary bone was reconstructed and a standard 1-piece LeFort I osteotomy advancement was cut above the tooth roots according to the surgical plan (Fig. 2a). Isolated maxillary segments were moved forward with 9 mm advancements performed to understand the biomechanical influence with different fixation plate designs (Fig. 2a).

2.2. Bone plate/screw systems biomechanical analysis

Two types of bone plates made of pure titanium grade IV including a commercial straight mini-plate and continuous plate were designed to fix separate skeletal segments for the Le Fort I

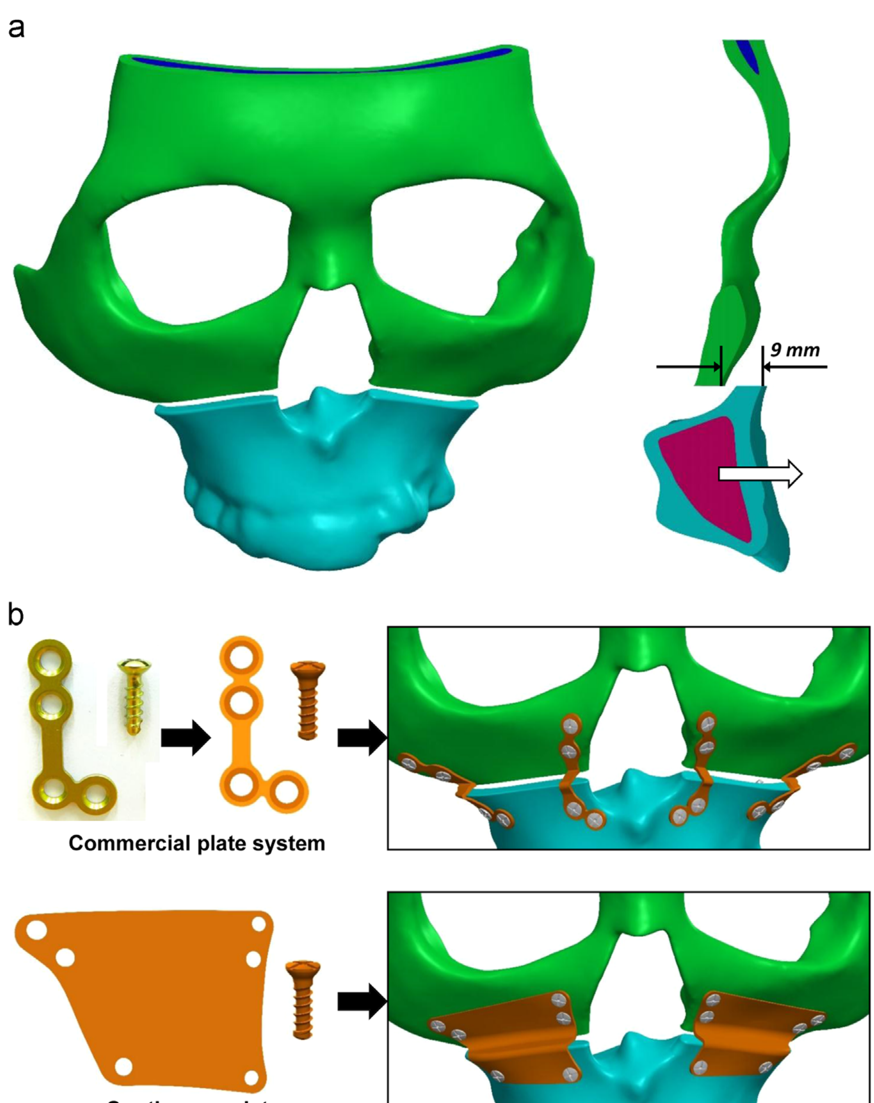

Fig. 2. (a) Left part of the Le Fort I osteotomy solid model and corresponding model for advancements with 9 mm distances. (b) Le Fort I osteotomy maxillary bone solid model assembly fixed with commercial plate system and continuous plate.