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Short communication

Finite element analysis of customized reconstruction plates for mandibular continuity defect therapy

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ABSTRACT

Large mandibular continuity defects pose a significant challenge in oral maxillofacial surgery. One solution to this problem is to use computer-guided surgical planning and additive manufacturing technology to produce patient-specific reconstruction plates. However, when designing customized plates, it is important to assess potential biomechanical responses that may vary substantially depending on the size and geometry of the defect.

The aim of this study was to assess the design of two customized plates using finite element method (FEM). These plates were designed for the reconstruction of the lower left mandibles of two ameloblastoma cases (patient 1/plate 1 and patient 2/plate 2) with large bone resections differing in both geometry and size. Simulations revealed maximum von Mises stresses of 63 MPa and 108 MPa in plates 1 and 2, and 65 MPa and 190 MPa in the fixation screws of patients 1 and 2. The equivalent strain induced in the bone at the screw-bone interface reached maximum values of 2739 micro-strain for patient 1 and 19,575 micro-strain for patient 2. The results demonstrate the influence of design on the stresses induced in the plate and screw bodies. Of particular note, however, are the differences in the induced strains. Unphysiologically high strains in bone adjacent to screws can cause micro-damage leading to bone resorption. This can adversely affect the anchoring capabilities of the screws. Thus, while custom plates offer optimal anatomical fit, attention should be paid to the expected physiological forces on the plates and the induced stresses and strains in the plate–screw–bone assembly.

1. Introduction

Clinical experience and prevalent literature have shown that the commercially available stock titanium reconstruction plates currently used for mandibular defects are often subject to excessive stress that may lead to fatigue fractures (Atilgan et al., 2010; Probst et al., 2012; Wagner et al., 2002). One method of estimating fatigue fracture is the use of preoperative finite element analysis that allows for a reliable analysis of possible stress factors (Costa et al., 2012; Kavanagh et al., 2008; Martola et al., 2007; Wirth et al., 2010).

When planning complex reconstructive surgery using either autologous bone or tissue engineered constructs, it is often not possible to reproduce complex facial contours with stock plates and meshes. These plates are designed for the 'average' patient, and are supplied as straight or slightly contoured metal plates with preformed retention screw holes in only generic shapes and sizes. During surgery, the surgeon may have to spend a considerable amount of time bending and shaping the plate to fit the contour of the patient's bone. The use of stock plates in simple surgical procedures offers good results in straightforward cases. In complex cases, however, stock plates often lack passive anatomical fitting that can be overcome by using patient-specific plates. Rapid prototyping offers preoperative fabrication of patient-specific, hence customized (Cohen et al., 2009; Lethaus et al., 2012; Sun and Zhang, 2012) reconstruction plates using the patient's clinical image data.

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Numerous rapid prototyping methods have been developed for the fabrication of medical appliances (Goiato et al., 2011; Hollander et al., 2005; Leiggener et al., 2009). While reconstruction plates can be fabricated with great efficiency, to the best of our knowledge there is no standardized methodology for the design of customized plates. This opens up questions regarding the structural design of plates (Metzger et al., 2011) and their limitations in terms of structural performance such as flexibility, strength, fixation, and the interaction between screws and bone tissues (MacLeod et al., 2012). This warrants a holistic approach to the design of plates where biomechanics theory must be incorporated in formalizing reconstruction plate design paradigms (Kang et al., 2012). To date, very little information exists on the influence of design on the clinical outcome of customized plates.

In the following sections, we present our assessment of the implant design of two structurally different customized reconstruction plates using finite element models. The aim of this study is to emphasize the advantages of the customized, rapid prototyped approach, while, at the same time, laying a basis for the formal performance evaluation of plate designs.

2. Material and methods

2.1. Materials

Two patients with ameloblastomas that required segmental mandibular resection and simultaneous reconstructive surgery of the lower left mandible were included in this study. Stereolithographic skull models were fabricated using the patient's computed tomography (CT) image data, and used to assess the planned resection defects. The patient CT datasets were subsequently imported into ProModel Romexis virtual surgical planning software (Planmeca, Finland). Patient-specific, three-dimensional reconstruction plates were designed by three surgeons and one engineer (Fig. 1) based on the clinical experience of the performing surgeons. The virtually designed plates were then converted into stereolithography (STL) format and exported to a proprietary laser sintering device.

2.2. Mechanical testing

The plates were subjected to stand-alone mechanical compression tests to verify their behavior under forces that mimicked simple physiological loads. Mechanical testing of the plates was performed using a unidirectional load-testing device (Lloyd LR30K, Lloyd Instruments Ltd., UK).

2.3. Finite element analysis

The anatomical geometry of the mandible for each patient was obtained from CT image data (patient 1 – female/49 years; patient 2 – male/47 years) through segmentation and conversion to STL file format. Resection of the mandible at the tumor site was made in concordance with the performed surgery for each individual patient in SolidWorks 2010 (Dassault Systèmes, France). The geometries of the customized plates were directly available as STL files from their design phase. The main differences between the plates were in length and the number of fixing screws. Plate 1 extends from the mandible body to the condyle, replacing the mandible angle. Plate 2 extends from the chin to the mandible angle, replacing the mandible body. Using ANSYS (ANSYS Inc., USA), solid objects (mandible, screws and plate) were meshed by 10 node quadratic elements. The plate-bone and screw-bone interfaces were meshed using 8 node quadratic surface to surface elements by friction contact with coefficient 0.3 (Shirazi-Adl et al., 1993; Viceconti et al., 2000). A sensitivity analysis of element size was performed for both models and one million elements were deemed optimal.

Material characteristics for bone were obtained from Schwartz-Dabney and Dechow (2003) and detailed in Vajgel et al. (2013). Cortical bone was modeled as

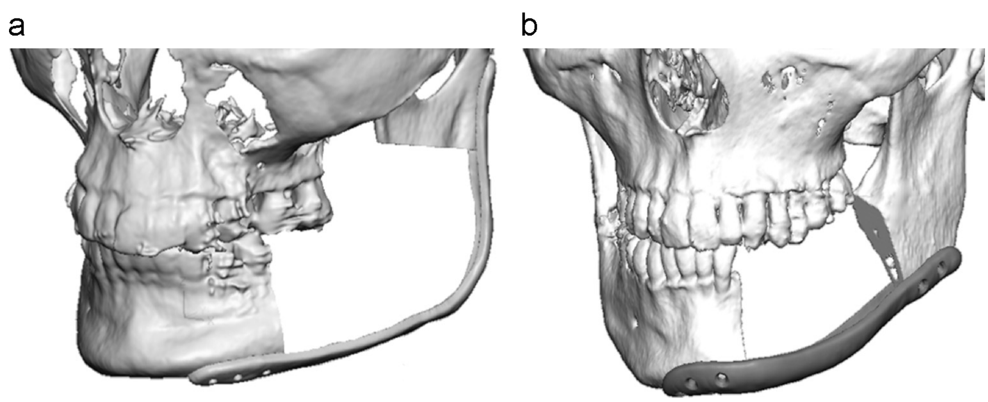

Fig. 1. Virtual models demonstrating the planned mandibular resection and corresponding reconstruction plates for the two patients—(a) reconstruction plate 1, (b) reconstruction plate 2.

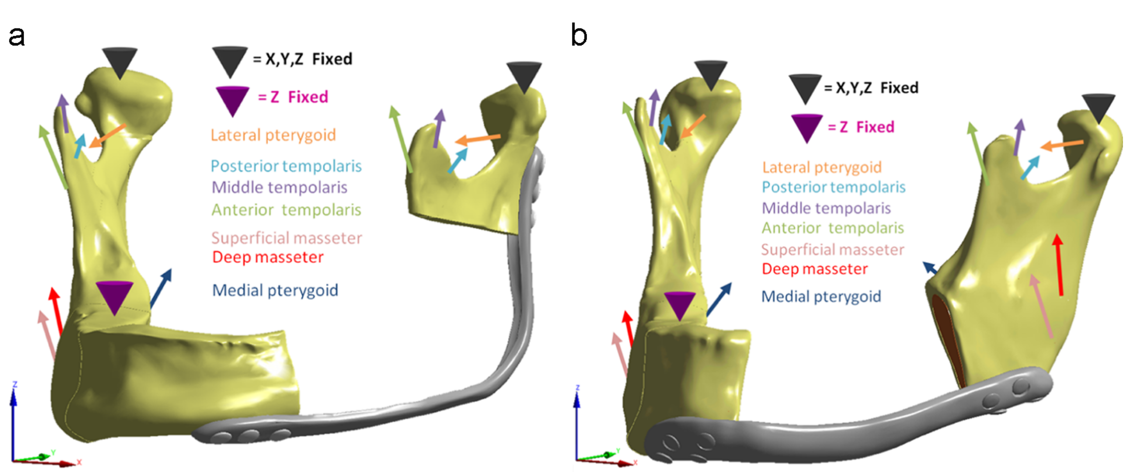

Fig. 2. Schematic for the boundary conditions and loads for (a) reconstruction plate 1 and (b) reconstruction plate 2. The setup simulates unilateral chewing at the molars of the healthy side of the mandible. Values and direction of the muscle forces are based on literature (Vajgel et al., 2013).