Medical Engineering and Physics 000 (2018) 1–8

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Biomechanical analysis of bone remodeling following mandibular reconstruction using fibula free flap

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ARTICLE INFO

Article history:
Received 8 September 2017
Revised 24 February 2018
Accepted 13 March 2018
Available online xxx

Keywords:
Fibula free flap
Finite element analysis
Jaw biomechanics
Mandibular reconstruction
Bone remodeling

ABSTRACT

Whilst the newly established biomechanical conditions following mandibular reconstruction using fibula free flap can be a critical determinant for achieving favorable bone union, little has been known about their association in a time-dependent fashion. This study evaluated the bone healing/remodeling activity in reconstructed mandible and its influence on jaw biomechanics using CT data, and further quantified their correlation with mechanobiological responses through an *in-silico* approach. A 66-year-old male patient received mandibular reconstruction was studied. Post-operative CT scans were taken at 0, 4, 16 and 28 months. Longitudinal change of bone morphologies and mineral densities were measured at three bone union interfaces (two between the fibula and mandibular bones and one between the osteotomized fibulas) to investigate bone healing/remodeling events. Three-dimensional finite element models were created to quantify mechanobiological responses in the bone at these different time points. Bone mineral density increased rapidly along the bone interfaces over the first four months. Cortical bridging formed at the osteotomized interface earlier than the other two interfaces with larger shape discrepancy between fibula and mandibular bones. Bone morphology significantly affected mechanobiological responses in the osteotomized region ($R^2 > 0.77$). The anatomic position and shape discrepancy at bone union affected the bone healing/remodeling process.

1. Introduction

Free vascularized osteocutaneous tissue transfer has become a well-established procedure for maxillomandibular reconstruction following large resection due to trauma, atrophy, and tumors ablation [1,2]. Fibula free flap (FFF) provides superior length and long vascular pedicles for mandibular reconstruction, with proven subsequent high reliability and adaptability [3]. Nevertheless, some clinical complications remain with delayed or poor union between the grafted fibula bone and host native mandible [4,5]. Recent CT evaluations reported 20% [6] and 9% [7] non-union rates, respectively. Bone union determines the strength and health of the reconstructed mandible, both of which are essential for further occlusal and prosthetic rehabilitation. In the case of bone fracture healing, the mechanobiological environment, which is thought to regulate cellular behaviors, can be a critical determinant [8].

Unlike general bone fracture healing processes, FFF mandibular reconstruction may be affected by additional factors, such as shape discrepancy between different bones and poor bone vascularity [4,9]. Further, the loss of several masticatory muscles due to resection can cause unbalanced jaw movement and abnormal mastication, leading to significant change in the biomechanical conditions [10,11]. Thus the mechanobiological responses in the jaw can be altered significantly; and such a change in-turn affects subsequent bone remodeling activities [12,13]. To assist surgical planning and oral rehabilitation it is essential to understand bone healing/remodeling activity and its influence on jaw biomechanics, thereby preventing delayed or poor union of bone grafts.

Finite element (FE) analysis has the adequacy for the biomechanical studies on orthopaedic [14–16] and dental problems [17–19]. Several those studies demonstrated their compelling

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https://doi.org/10.1016/j.medengphy.2018.03.008
1350-4533/

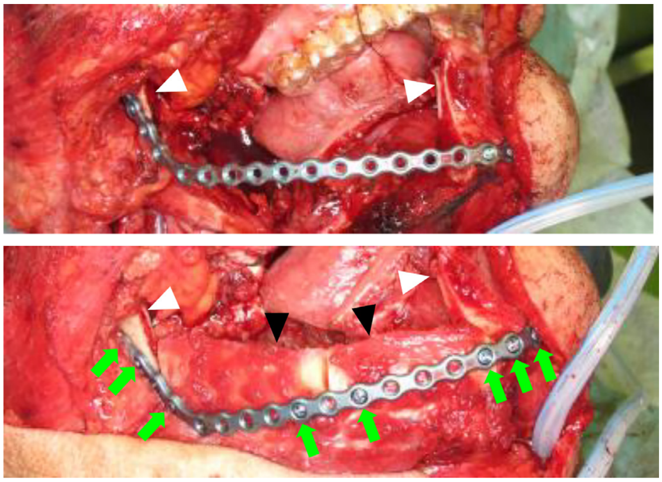

Fig. 1. Intraoperative view illustrating the fibula bone affixed to the titanium fixation plate.
White triangle: mandibular bone, Black triangle: fibula bone. Green arrows: Screw position (8 of 11 screws are shown in this picture). The flap pedicles were anastomosed with the thyroid artery and the external jugular vein. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

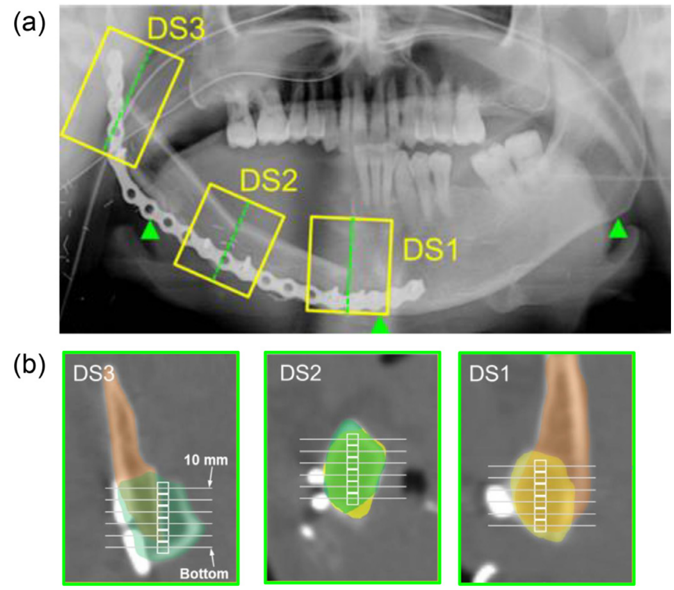

Fig. 2. Clinical X-ray and CT images for assessment.
(a) Postoperative radiograph (M0). Yellow boxes: three investigated docking sites (DS1, DS2 and DS3) for the bone union. Green triangles: reference points for defining mandibular plane for 2D MPR (multiple planar reconstructions) analysis. (b) CT MPR cross-sectional images of contact interface perpendicular to the mandibular plane (green line in (b)) at three docking sites at M0; brown: mandible, yellow: anterior fragment of fibula bone, green: posterior fragment of fibula bone. Lateral lines: planes for analysis, boxes: cubic (2 mm^3) volume of interests (VOIs). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

advantages for understanding the biomechanics and mechanobiology of reconstructed mandibles *in-silico* [20,21]. With recent advances in micro computerized tomography (CT), bone mineral density (BMD) and morphological changes can be measured to evaluate bone remodeling sequences noninvasively [13,22,23]. The CT-based 3D FE models can be thus created to quantify biomechanical responses to functional forces in a patient-specific and time-dependent manner [24,25].

This study aims to (1) examine longitudinal changes in bone morphology and mineral density in the course of healing/remodeling after mandibular reconstruction with FFF; and (2) investigate the associated variation in mandibular biomechanics in terms of mechanical stimulus. The postoperative CT scans were performed at 4 critical time points over two and half years' clinical follow-up, and the CT images were segmented for both 2D multiple planar reconstructions (MPR) and 3D (volumetric) analyses. The bone condition was analyzed in both spatial and temporal manner, in terms of morphology and BMD. Nonlinear 3D FE analyses were conducted to quantify the bone mechanobiological stimuli at these different time points; and then correlated to the corresponding *in-vivo* clinical data. By establishing this combined *in-vivo* and *in-silico* approach, the mutual influence between tissue conditions and mandibular mechanobiology was assessed. The results are expected to provide important insights into surgical plan for mandibular reconstruction.

2. Materials and methods

2.1. Clinical treatment

A 66-year-old male patient received mandibular reconstruction with osteotomized FFF, due to a squamous-cell carcinoma at the right molar gingiva at the Department of Otolaryngology-Head and Neck Surgery, Tohoku University Hospital in Japan. Upon harvesting, the fibular bone was segmented to match the defect jaw morphology. A titanium fixation plate (Synthes, Solothurn, Switzerland), which was pre-bent using the CT-based 3D patient model before surgery, was configured to be fixed monocortically with a total of 11 titanium screws (Synthes, Solothurn, Switzerland) as shown in Fig. 1. The first CT scan (M0) was performed at the end of surgery, and the follow-up CTs were taken at 4, 16 and 28 months after surgery (namely, M4, M16, and M28, respectively). A removable partial denture was inserted into this subject 6 months after the surgery; however, the subject did not use it for mastication, due to fear of biting on the reconstructed side. The periodontal conditions of the remaining teeth and the removable partial denture have been maintained at the Maxillofacial Prosthetics Clinic in Tohoku University Hospital every three months.

2.2. CT imaging acquisition and 2D image analysis

Multi-detector helical CT scans were performed for the follow-up examinations using Somatom Emotion 6 (Siemens, Erlangen, Germany) at 120 kV and 80 mA with the spatial resolution of 0.4, 0.4, and 0.8 mm in the radial, tangential, and axial directions. The CT data was further processed with the medical image viewer software (EV Insite S, PSP Co., Tokyo, Japan), for the detection and alignment of anatomic landmarks between the different cross-sectional examinations. The mandibular plane was defined using three reference points; namely, left Gonion point, Menton point, and inflection point of a titanium fixation plate (green triangles in Fig. 2a). Six planes parallel to this mandibular plane were selected for the quantitative analysis of bone union at three docking sites (DS1, DS2, and DS3, respectively) with 2 mm intervals by multiple planar reconstructions (MPR) (Fig. 2b) [12]. On each plane, a 2 mm^3 volume of interest (VOI) was considered along the superior-inferior axis (Fig. 2b). Since a significant correlation between Hounsfield units (HU) obtained from clinical CT scans and bone mineral density (BMD) were established [26], the HU values change in VOIs can be regarded as the BMD changes over time here, particularly for bone unification at the contact interfaces. All the VOIs were placed at the same positions throughout these four time points, based on the distance from the titanium fixation plate and screws as a reference.

Please cite this article as: N. Yoda et al., Biomechanical analysis of bone remodeling following mandibular reconstruction using fibula free flap, Medical Engineering and Physics (2018), https://doi.org/10.1016/j.medengphy.2018.03.008