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Identifying Mini-Plate Configurations with High Predicted Bone Union Propensity for Mandibular Reconstruction Surgery

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Abstract

Mandibular reconstruction with bone grafts remains the gold standard for restoring masticatory function and facial aesthetics in patients with jaw defects. However, definitive guidelines for selecting plate types and fixation strategies remain lacking. This study evaluates different miniplate configurations to optimize bone union propensity (BUP) using physics-based simulation and finite element modeling. Various plate placements and screw configurations, covering a total of 10 cases, were tested to assess their impact on strain energy distribution and bone healing potential. The results indicate that miniplates with four screws provide superior stability and that higher placement enhances fixation. These findings contribute to refining patient-specific reconstruction strategies and improving surgical outcomes.

1 Introduction

Mandibular reconstruction is a vital surgical procedure for restoring function and aesthetics in patients with advanced head and neck cancers in which a segment of the patient's fibula or scapula is used to fill the defect left after resection of the tumour [1, 2]. Over the past few years, our group has been using virtual surgical pre-planning and 3D printed cutting guides to guide the reconstruction, and full-length reconstruction plates to secure the donor segment in place. More recently, we have been developing a "day-of-surgery" system in which we use surgical navigation techniques to plan the bone cuts intraoperatively [3], and are seeking to reduce the intrusiveness of the reconstruction plates by replacing them with miniplates which span each junction between bone segments. Traditional plates often suffer from poor anatomical fit, alignment challenges, and interference with graft vascularization, leading to complications such as infections, plate exposure, and delayed or failed bone healing [4]. Miniplates, with their smaller size and greater adaptability, show promise in addressing these issues, but their impact on bone healing and integration remains insufficiently studied [5].

In recent work, Aftabi et al. [6, 7] have presented a modeling technique aimed at predicting the propensity to achieve bony union following surgery and have found that the orientation of bone cuts

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strongly affects the predicted propensity, but have not yet applied this technique to analyzing miniplate constructs. In this study, therefore, we seek to identify promising miniplate designs and configurations to use with our day-of-surgery system by simulating a single chewing cycle to predict which areas of each construct will reach strain energy densities known to promote bone growth. Our ultimate goal is to leverage these insights to create reconstruction plans that enhance bone healing and improve surgical outcomes.

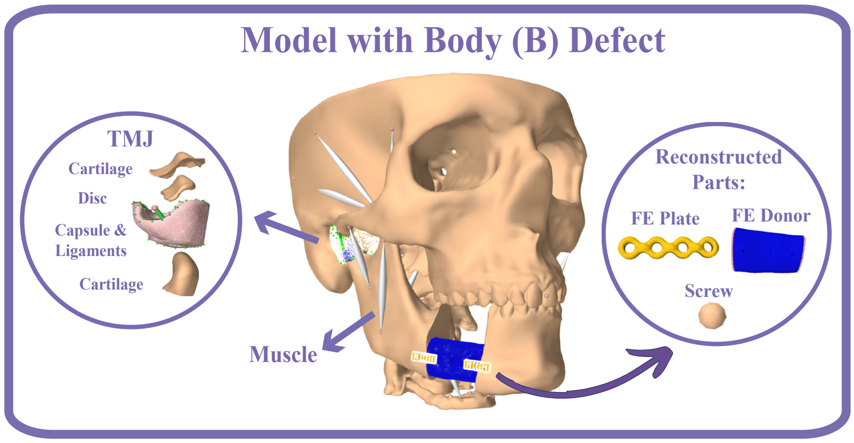

Figure 1: **Body Defect Model with Mid-Positioned Miniplate.** The model comprises a combination of rigid and deformable components, with the mandible, maxilla, and hyoid, and screws treated as rigid bodies, while the temporomandibular joint, donor segment, and plate are modeled using finite elements.

2 Methods

The study workflow comprised three stages: plate design, virtual reconstruction, and biomechanical simulation, applied to a mandibular body defect (B defect) using our previously developed jaw model (see Section 2.3).

2.1 Plate Design

Generic miniplates (2 mm hole diameter, 8 mm spacing, 1 mm thickness) were tested in various configurations (see Figures 1 and 2), varying in plate positioning, screw placement, and geometry. Miniplates were positioned at high, mid, or low heights to assess vertical placement effects on bone fixation, while screw configurations varied in number and spacing. Additionally, square and rectangular plates were designed in SolidWorks, along with an end-to-end standard plate (also known as a reconstruction plate) [8] as the baseline, totaling 10 cases for comparison.

2.2 Virtual Reconstruction

Mandible and fibula CT scans were segmented in 3D Slicer [9] and imported into ArtiSynth [10] to construct the B defect [6]. The fibula, mandible, and cut planes were integrated, and a plate was aligned with their contours. MeshLab [11] was used for isotropic explicit remeshing, optimizing vertex distribution.

2.3 Biomechanical Simulation

The biomechanical model [12, 6] (see Figure 1) included rigid structures (mandible, maxilla, hyoid), extensible ligaments, Hill-type muscles, and a finite element representation of the temporomandibular joint, donor segment, and plate. Rigid 7 mm locking screws, modeled as rigid bodies, secured the titanium plate with hexagonal finite elements by linking adjacent hex elements to screws and rigidly attaching it to the mandible. ArtiSynth's collision detection and an elastic foundation layer modeled realistic contact between the cortical donor [6] and native mandible [10]. Chewing forces of 110 N were applied to the left first molar, and different plate designs were tested over a chewing cycle. This value reflects the average chewing bite force recorded on the reconstructed mandible's contralateral side [12].

Bone healing likelihood was assessed using strain energy density (SED) relative to apparent bone density, following established remodeling principles [13, 14, 6]. The analysis focused on a single layer of finite elements along each side of the donor, where SED was computed and normalized as:

$$S = \frac{\frac{1}{2}\sum_{i=1}^{3}\sum_{j=1}^{3}\sigma_{ij}\epsilon_{ij}}{\rho} \tag{1}$$

where σ_{ij} and ϵ_{ij} are the stress and strain tensors, and ρ is the apparent bone density. Healing was expected when $S > S_0(1+\delta)$, with $S_0 = 0.036\,\text{mJ/g}$ and $\delta = 0.1$ [6]. Bone apposition is predicted to accelerate once this threshold is met. Bone union propensity (BUP) is defined as the average percentage of elements with normalized SED above this threshold within a single layer, averaged over one chewing cycle, with muscle activations set to pre-reconstruction levels To model the early rehabilitation and recovery stages [6].

3 Results

Figure 2 shows the bone union propensity (BUP) for the tested miniplate designs, incorporating variations in plate positioning, shape, and screw placement. The graphs depict BUP for the left and right sides during a single chewing cycle, ranking designs from best to worst. The 4-hole mini-plate with 4 screws achieved the highest predicted BUP compared to the standard plate, with an average of 78.1% and 86.9% over one chewing cycle for the left and right surfaces, respectively. This may be attributed to the increased stiffness resulting from the higher number of plates, as well as the additional screws, which generate localized stress and strain, potentially promoting bone healing. For this specific defect (B Defect), a top plate position provided better bone stability, suggesting that higher placement enhances fixation. More screws also improved bone union, which emphasize the importance of secure fixation.

Overall, more rigid designs, such as mini-plates with four holes (two per side of each interface) or four miniplates with two holes each, had higher predicted BUP scores than less rigid designs. Square and rectangular plates showed mid-range BUP scores. Regardless of hole count, higher plate placement consistently led to better BUP outcomes than lower placement.

4 Discussion and Conclusion

In this study, the biomechanical integration and the potential of various miniplate designs to enhance bone healing in mandibular reconstruction were explored. Different plate designs and configurations, including a conventional four-hole miniplate and arbitrary designs such as rectangular or square-shaped plates, provided critical insights into which configurations might enhance bone healing and potentially improve surgical outcomes. Notably, the results suggest that, all else being equal, miniplates equipped with four screws should be preferred over those with only two for enhanced stability and healing. Additionally, when employing single plates at each junction, higher placement on the bone segment is advisable over lower placement which is also shown in previous work by Joshi & Kurakar [15]. Although they found that the number of screws did not significantly alter overall mechanical stability,

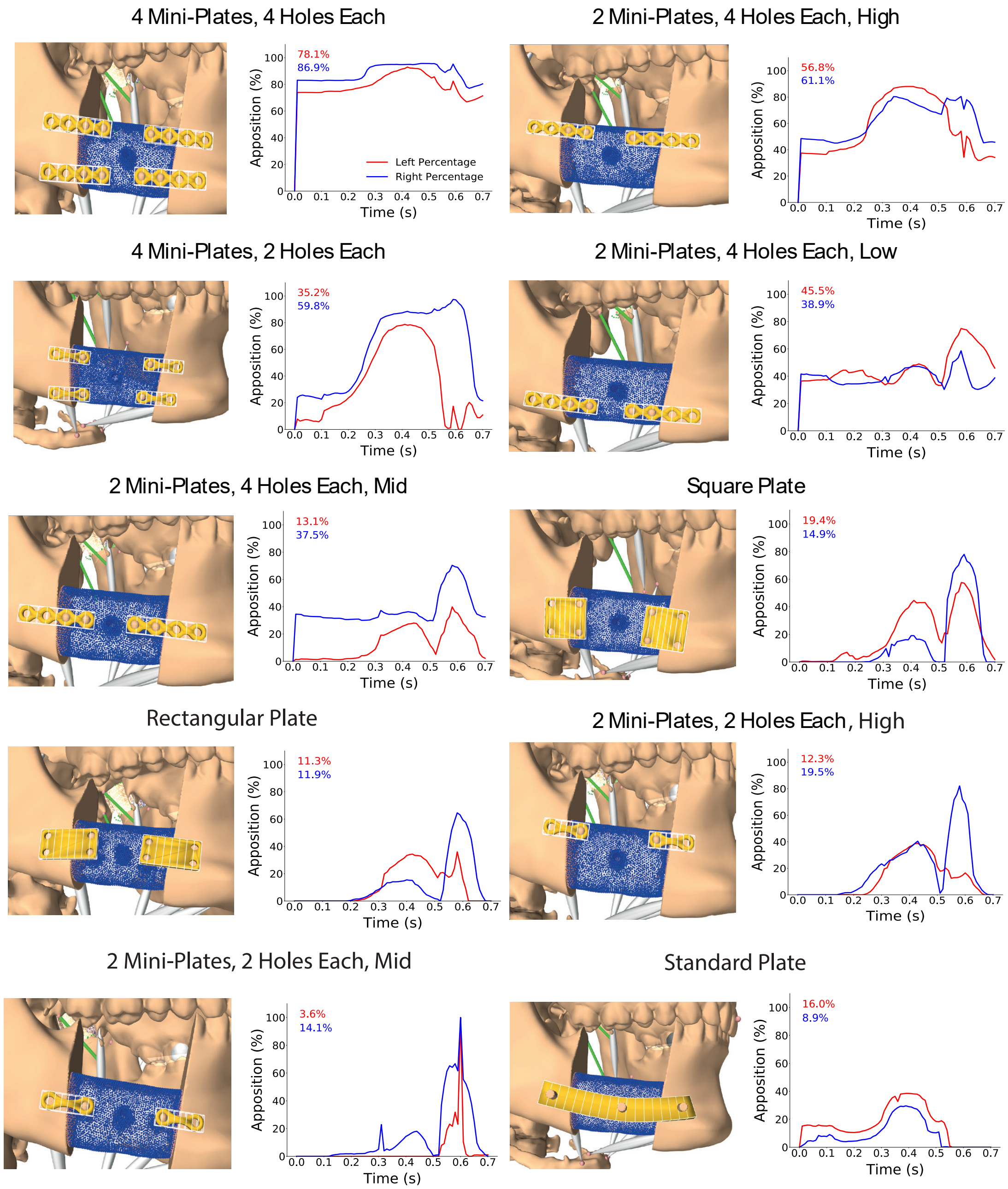

Figure 2: **Bone Union Propensity (BUP) Across Miniplate Designs.**. Average BUP values are shown for the left and right donor-bone interfaces during a single chewing cycle. Colors indicate the respective sides (left = blue, right = red). BUP is defined as the percentage of finite elements in the contact layer that exceed the normalized strain energy density threshold $S_0(1+\delta)$, where $S_0 = 0.036\,\text{mJ/g}$ and $\delta = 0.1$. Labels at the top right of each graph display the average BUP for each side.

the localized stress concentrations generated at each screw–bone interface may act as a mechanical stimulus for osteogenic activity, thereby enhancing callus formation and accelerating bone healing.

Aftabi et al. [6, 7] have previously demonstrated that modifying the donor cut planes can significantly enhance BUP. This principle is applied here to plate configurations, as shown in Figure 2. In the bottom right corner of the figure, the Standard Plate results in a lower BUP compared to other Plate Configurations, highlighting the importance of exploring different plate designs to enhance bone union.

Despite the promising results, this study is not without limitations. The predicted Bone Union Propensity (BUP) scores are based on bone growth models validated in several settings [13, 14], yet these predictions have not been validated in vivo. Moreover, the study employs modeling simplifications that might not accurately reflect clinical realities, such as the assumption of perfect bone cuts and reconstructions, as well as rigid connections between the screws and bones. Furthermore, the range of miniplate designs tested was limited. Future research should explore a broader array of design parameters, particularly focusing on screw hole locations and the combined effects of cut angles, positions, and plate designs. As Aftabi's work suggests, cut angles significantly influence the predicted BUP scores.

The potential value of this work is substantial, suggesting that once validated, it could significantly inform future plate designs to minimize or prevent non-union following mandibular reconstruction surgery and reduce soft tissue damage associated with the size and intrusiveness of the plates.

In summary, this study suggests that using miniplates with four holes each, either in pairs across each bone interface or singly placed high on the mandible, may enhance the probability of achieving bony union. Future research should aim to validate these predictions through empirical testing.

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