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Numerical Study of Mechanical Development of Patient-Specific Mandibular Reconstruction Implant

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ABSTRACT

Introduction: Patient-specific mandibular reconstruction implants are a new technique to deal with ameloblastoma tumors. Although they could solve the integration problem which is attributed to the graft reconstruction approach, they may increase the risk of infection due to poor blood supply around it. Using bone grafts besides customized plates with smaller geometries would be considered as an alternative. However, they would also have possible complications like poor graft integration and plate fracture. Considering weight reduction patterns on implants would efficiently help to solve the mentioned problems.

Materials and Methods: In this study, two design concepts of mandibular reconstruction implants which were different in weight reduction pattern's location were presented. Also, a finite element assessment was performed to evaluate the mechanical performance and functionality of the implants under chewing load.

Results: Results revealed that designing patterns all over the implant geometry would lead to minimum jaw deviation and maximum Von Mises stress values around 120 MPa which is much less than Ti6Al4V yield stress.

Conclusion: Compared to the solid design, the patterns would enhance the implant function by decreasing the deviation which would result in a function similar to the intact side. Although results showed the proper functionality of the implant clinical trials with multiyear follow-ups are still needed to investigate the detailed clinical results of this concept.

Keywords: Biomechanics; Finite element analysis; Patient-specific implants; Customized implants; Reconstruction surgery; Ameloblastoma tumor.

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Introduction

Ameloblastoma tumor is a common oral defect that could be treated with surgical resection followed by reconstruction using autografts and reconstruction plates [1,2]. Although this technique is the gold standard for treating these defects, many postoperative complications of this method including poor graft integration and nonsymmetrical facial contour have been reported [3,4]. Customized implants are another alternative that can provide full symmetric buccal contour [5]. The integration is not a concern anymore; however, they are usually much heavier than the bone and their size and extent prevent proper blood supply around it which would result in infection and exposure [6–9]. Considering weight-reduction patterns on implant geometry would solve this problem to some extent whereas it may affect the structural integrity and strength of the implant [10].

Past studies reported that using custom-made plates with smaller geometries besides vascularized bone grafts would be a better choice which would possess the advantages of both methods. However, this approach may also increase the operation time and has the potential of poor graft integration and plate fracture [11]. Finite element analyses and topology optimization on mandibular reconstruction plates were performed to increase their functionality; however, studies were limited to plates that have simple geometries [12–15]. This study aims to perform finite element analyses to evaluate the mechanical performance of two design concepts of condylar mandibular reconstruction implants which are different in their weight-reduction pattern's location.

Materials and Methods

3D DICOM of CT scan images (0.5mm thickness) of an anonymized patient who had been diagnosed with an ameloblastoma tumor and undergone segmental mandibulectomy and reconstruction surgery using a reconstruction plate were used to create the geometrical model of the mandible and the implant. Bone Segmentation and implant design processes were performed respectively in Mimics and 3Matic software (Materialise, Leuven, Belgium). A solid condylar partial mandibular implant was designed for the patient which restores the buccal contour and mandible function and covers the chin up to near the mental foramen which then can be fixed there using nine mono-cortical screws with 2mm diameter (Figure 1a). The implant geometry conforms to the mirror side of the intact mandible which would result in a full symmetric buccal contour. The mirror plane was verified by anatomical landmarks such as Porion, zygon, Nasion, and Orbitale. The thickness of the implant in the ramus region is in accordance with the patient morphology. However, in the body, the thickness was reduced from the lingual side to decrease to risk of gingiva damage and dehiscence. The assembly including mandible, implant, and screws were imported in ABAQUS software (Simulia, Rhode Island, United States). The standard static simulation was used to calculate the resulting Von Mises stress distribution on the implant besides its translational displacement in Z direction (According to global coordinate system) to investigate the jaw deviation. Three design concepts that were different in terms of weight-reduction patterns were considered to evaluate the PSI performance under chewing load. One design was solid and without any weight-reduction pattern (Figure 1a). The other had triangular patterns at the body only and the third design consists of these patterns at the body and ramus (Figure 1b and c). in all concepts, a minimum 2mm thickness of the implant was considered to ensure the perseverance of implant structural integrity. Material properties for the screws and the implant were specified as isotropic Ti6AL4V, and for the mandible, the general cortical bone properties were applied [16,17]. The mechanical properties of the models have been listed in Table 1.

Standard surface-to-surface (Master-Slave) contact with hard contact normal behavior and 0.8 friction tangential behavior was defined for contact areas, including bone-implant and bone-screws interface. Whereas, for interface areas between the implant and screws the tie constraint was considered. Fixed boundary condition was attributed to the temporomandibular joint region and a 600 N axial force (in the Z axis of the global coordinate system) was applied to a reference point located in the middle of the anterior teeth which was constrained using multiple point constraint (MPC) with all anterior teeth to simulate the load distribution on them [18,19] (Figure 2). Adaptive triangular gradient surface mesh was generated for models (minimum edge length: 0.5mm, Maximum edge length: 1.5mm) and non-structured three-dimensional four-node tetrahedral (C3D4) element volume mesh was constructed for all models (maximum edge length:2.5mm)

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Table 1. Mechanical properties of different parts of the model.

Material	*Density (g/cm^3)*	*Elastic Modulus (MPa)*	*Yield strength (MPa)*	*Poisson's Ratio (v)*
Mandible	*1.8*	*18,300*	*-*	*0.3*
Ti6Al4V	*4.43*	*110,000*	*1100*	*0.3*

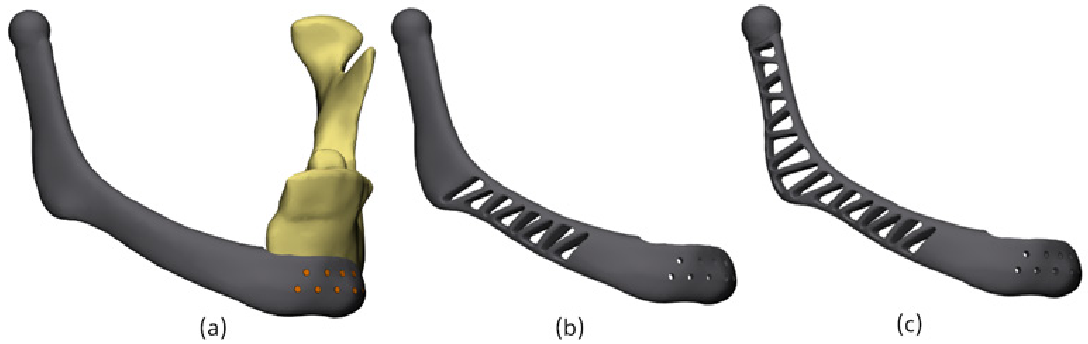

Figure 1. a) Concept without weight-reduction pattern, b) concept with weight-reduction pattern in body, c) concept with weight-reduction pattern in body, and ramus.

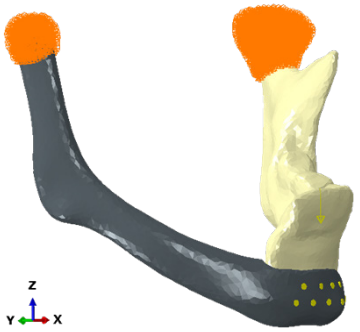

Figure 2. Boundary conditions and load application.

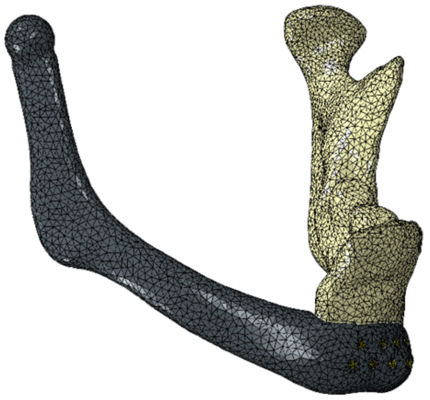

Figure 3. Mesh construction for parts.

Results

For each design concept, Von Mises stress distribution along with deflection contours was extracted. Patterns could reduce the weight of the implant by approximately 13% and 28% respectively (Table 2). Results for solid design illustrate that the maximum stress with an approximate amount of 190 MPa would occur in the ramus region, particularly at anterior and posterior sections which bear the bending momentum resulting from the chewing force (Figure 4a). Contours also demonstrate around 120 MPa stress in the superior and inferior section of the body, where it attaches to the ramus and angle. The same fashion was observed in the same locations when the weight-reduction pattern was considered in the PSI body (Figure 5a). However, the amount of resulting stress was highly affected and jumped from 120 MPa to 190 MPa, especially at inferior and superior borders. Also, stress concentration was observed in a few elements with an approximate amount of 340 MPa. For a concept that has a pattern in the ramus and body, the 3D contours presented an exciting low amount of stress values with a maximum of around [110-120]. MPa which was located in the ramus region (Figure 6a). In other regions, the stress values did not exceed 80 MPa.

The deflection contours revealed that without considering the pattern the deflection would reach its minimum with a value of around 1.52mm (Figure 4b). However, it became greater by placing weight-reduction pattern reaching the amount of 2.9mm (Figure 5b and 6b). Also, it was observed that deflection contours were asymmetric with different values in angle regions for concepts without pattern and with pattern in the body while they were almost the same when considering pattern at ramus and body. The detailed results are reported in Table 2.

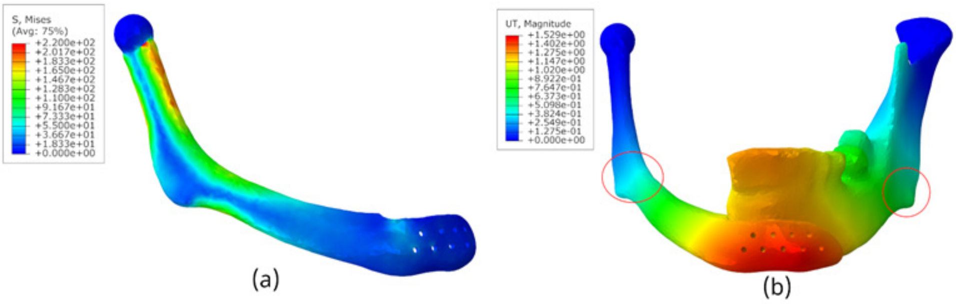

Figure 4. a) 3D contour of Von Mises stress for concept without weight-reduction pattern (MPa), b) Assembly deflection for concept without weight-reduction pattern.

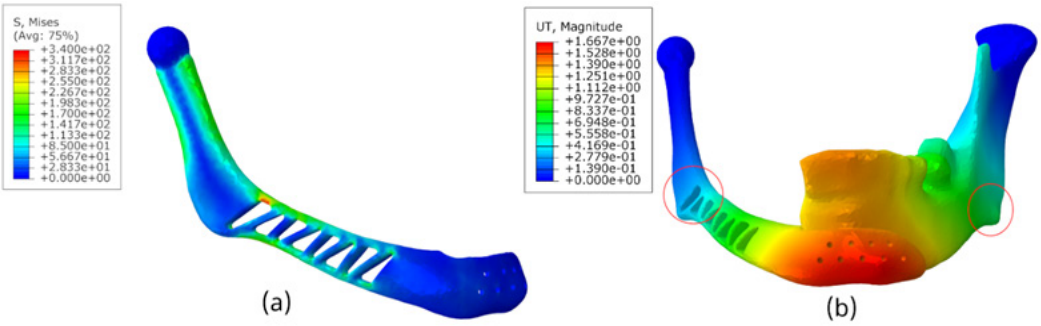

Figure 5. a) 3D contour of Von Mises stress for concept with weight-reduction pattern in body (MPa) b) Assembly deflection for concept with weight-reduction pattern in body.

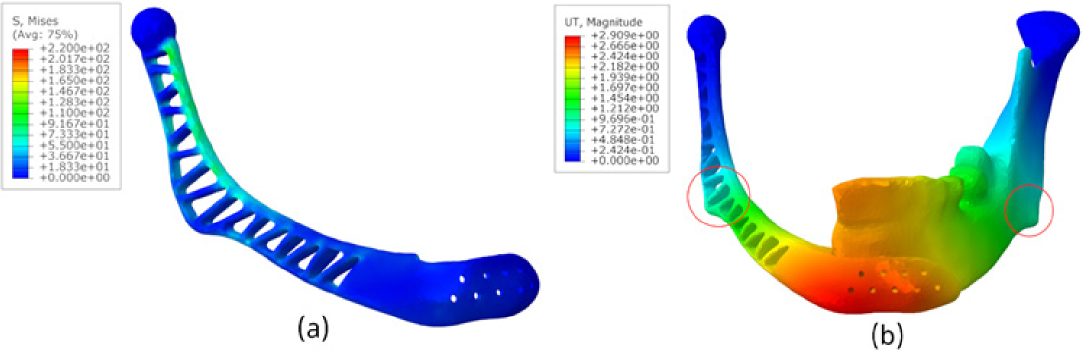

Figure 6. a) 3D contour of Von Mises stress for concept with weight-reduction pattern in body and ramus (MPa) b) Assembly deflection for concept with weight-reduction pattern in body and ramus.

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Table 2. Detailed results of concepts.

Pattern Region	*Weigh reduction Percentage*	*Max Von Mises Stress (MPa)*	*Max Stress Location*	*Max Deflection (mm)*
No Pattern (Solid)	*0*	*190*	*Ramus*	*1.52*
Body	*12.96*	*340*	*Ramus-Body junction*	*1.66*
Body and Ramus	*28.37*	*120*	*Ramus*	*2.9*

Discussion

In the design of customized mandibular implants, other weight-reduction patterns with various cell geometries could be used, but due to the clinical limitation of the risk of soft tissue indentation in these patterns which would result in asymmetric facial contour followed by patient complaint, it would not be possible to increase their width or design with larger cell size [20]. Also, the minimum critical thickness considered in these patterns is two millimeters, which would result in sufficient structural integrity.

Otherwise, it would probably cause high values of stress concentration and increase the risk of failure due to PSI fracture. Assigning material to the mandible could be done using patient-specific Hounsfield unit base assignment; however, it demands a large sample to study. Thus, the cortical mechanical properties were applied to generalize the material to the standard value. Results have demonstrated asymmetric deflection contours except in design with patterns in the body and ramus. This would be because of low stiffness due to the presence of weight-reduction patterns which provide the implant with a deflection pattern similar to the mandible without any deviation. On the other hand, in solid concept, the stiffness is high and it would result in the minimum deflection and maximum deviation compared to concepts with weight-reduction patterns.

In normal daily activities of healthy humans, the bite force could be in any direction and at various amplitudes ranging from 70 N to 900 N with an average of 430 N [18,19]. To achieve a reasonable safety factor in this study, the load amplitude was assumed to be 600 N which is much bigger than the average load. Also, according to the 3D stress contours, the maximum amount of stress in concepts was around [220-340] MPa. This amount of stress is much less than the Ti6Al4V yield stress (1100 MPa) in which fatigue would occur. Also, according to the Ti6Al4V SN diagram, for stress values around 350 MPa, the predicted life cycle exceeds the 10^{10} [21]. Taking into account, the 1050 chewing cycles per day for humans, the estimated life cycle for the implant under this load application would be infinite [22].

Conclusion

Patient-specific mandibular implants with weight-reduction patterns are a rational solution to increase blood supply to the surrounding tissues. The results of this study showed that despite the presence of the highest bending momentum in the ramus region of the implant, considering the triangular weight-reduction pattern in that region has resulted in acceptable stress values which are one-ninth of the Ti6Al4V yield stress. According to these results, the use of weight-reduction patterns in both the body and ramus region would not reduce the structural integrity of the implant and preserve its function as well as intact side without any deviation. However, finite element results would not be a sufficient criterion to prove the clinical success of this concept. Clinical trials and case series with multiyear follow-ups would be needed for detailed analysis of success rate.

Conflict of Interest

There is no conflict of interest to declare.

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