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Finite-element design and optimization of a three-dimensional tetrahedral porous titanium scaffold for the reconstruction of mandibular defects

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ABSTRACT

Reconstruction of segmental defects in the mandible remains a challenge for maxillofacial surgery. The use of porous scaffolds is a potential method for repairing these defects. Now, additive manufacturing techniques provide a solution for the fabrication of porous scaffolds with specific geometrical shapes and complex structures. The goal of this study was to design and optimize a three-dimensional tetrahedral titanium scaffold for the reconstruction of mandibular defects. With a fixed strut diameter of 0.45 mm and a mean cell size of 2.2 mm, a tetrahedral structural porous scaffold was designed for a simulated anatomical defect derived from computed tomography (CT) data of a human mandible. An optimization method based on the concept of uniform stress was performed on the initial scaffold to realize a minimal-weight design. Geometric and mechanical comparisons between the initial and optimized scaffold show that the optimized scaffold exhibits a larger porosity, 81.90%, as well as a more homogeneous stress distribution. These results demonstrate that tetrahedral structural titanium scaffolds are feasible structures for repairing mandibular defects, and that the proposed optimization scheme has the ability to produce superior scaffolds for mandibular reconstruction with better stability, higher porosity, and less weight.

1. Introduction

Mandible defects usually result from trauma, tumor resection, or osteomyelitis. Unrepaired defects can lead to disturbed masticatory function, loss of speech, and facial deformity, which can seriously affect the patient's quality of life. Thus, timely reconstruction is necessary, but remains a challenge [1]. The goal of mandibular reconstruction is to restore both the shape and function of the mandible. To date, many mandibular reconstruction methods have evolved, such as free bone grafts, pedicled bone grafts, particulate bone cancellous marrow, microvascular free flaps, modular endoprosthesis, and tissue engineered bone [2]. However, each method has disadvantages, and the ideal solution for mandibular reconstruction has yet to be found.

In recent years, an increasingly popular choice for segmental mandibular reconstruction is the use of titanium implants, including modular endoprosthesis and customized reconstruction plates [3–9]. A modular endoprosthesis consists of several solid titanium modules, which are assembled using a locking system and stably fixed onto the bone stumps. Although this method saves time and is cost-effective, there are some long-term complications, including loosening of the module connections and poor shape recovery [5,6,10]. In addition, the weight of the solid metal device might be too heavy to maintain facial balance, especially for large defects. Compared with a modular endoprosthesis, a customized reconstruction plate is better for bone surface adaptation and weight reduction [7,8]. However, screw-loosening and fracture often occur [8,9]. Another potential method for the reconstruction of mandible defects is tissue engineering. A tissue-engineered mandibular condyle, including bone and cartilage, has been reported [11–13]. A bone system from tissue engineering includes a biomaterial scaffold, usually an absorbable material, the seeded engineered bone marrow stromal cells, and osteogenic factors [1]. In these systems, the three-dimensional porous scaffold plays an important role in load support, shape recovery, cell support, guidance of new tissue generation, and nutrient transportation [14]. Yet, in most previous studies, the strength and shape of the absorbable material scaffold did not meet clinical requirements [11–13].

Compared with solid titanium implants, a porous titanium scaffold for tissue engineering is lighter and has a smaller elastic modulus, which helps avoid stress-shielding effects [15]. Compared with absorbable scaffolds, porous titanium scaffolds are more rigid

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and able to better withstand masticatory forces prior to bone formation [5,6,16,17]. Overall, a suitable balance between strength and stiffness would be conducive to bone regrowth, and enhanced bone fixation. Aside from material properties, the architectural structure of the scaffolds, determined by pore size and shape, is also a key point in the design, and directly determines the mechanical behavior of the bone/scaffold system [18,19]. With the development of additive manufacturing techniques, such as electron beam melting (EBM) and selective laser melting (SLM), porous open scaffolds of high mechanical quality with specific geometrical shapes and complex structures can be fabricated [20–22]. In previous studies, periodic lattice structures and Boolean operators were generally employed for scaffold design, and more attention has been paid to the analysis and optimization of the structural performance of these scaffolds. Wieding established three numerical models for open-porous scaffold designs: cubic, diagonal, and pyramidal. The geometrical parameters, like the strut diameter of scaffolds, were adjusted to approximate the elastic properties of human bone with suitable pore sizes [22]. Cheng presented a voxel-based homogenization topology optimization algorithm to optimize the scaffold structure so that they closely match the mechanical properties of the trabecular bone with the target material stiffness and the desired porosity [23]. Liu used image-based, computer-aided design and Boolean operators to create biomimetic scaffolds for mandibular defect repair [24]. Almeida applied a topological optimization during scaffold design to obtain the best topological architecture of the scaffolds under multiple different loading conditions and imposed additional constraints to ensure the integrity of the single-scaffold cells [25]. However, the properties of human bone vary between different body parts. As a result, optimization should be performed according to each specific bone defect. Moreover, the Boolean subtraction of the scaffold and the scaffold negative model can result in a step-like structure on the scaffold surface. Consequently, the free ends on the scaffold surface would give rise to problems in clinical practice. As the mandible is subjected to large, complex forces during mastication, a scaffold designed to replace a large segmental defect is often unable to provide long-term stability and a suitable environment for sufficient bone regeneration. To date, there are few scaffolds designed specifically for mandibular defects, not to mention optimized ones.

In this paper, a novel tetrahedral open-porous titanium structural scaffold in an anatomical shape was developed for repairing a large segmental mandibular defect. The proposed scaffold exhibited good interconnectivity and high porosity, with no stepped surfaces. The biomechanical behavior of the scaffold and the efficacy of repair were investigated with the finite-element method. An optimized method based on the principle of uniform stress was performed on the initial structure. Finally, the optimized scaffold, which was validated to insure maximum stability with minimal weight, might serve as a better endoprosthesis for mandibular reconstruction.

2. Materials and methods

2.1. Generation of the model geometry

The geometry of the model (Fig. 1(a)) was based on CT data from the mandible of a male volunteer, who had full dentition and no facial deformities. The CT data were imported into MIMICS (Version 10.01, Materialise, Inc., Leuven, Belgium) to reconstruct its geometry. By employing digital operations, such as the threshold segmentation method, regions of cortical bone, cancellous bone, and teeth were separated and reconstructed. After boundary smoothing and volume forming using Geomagic Studio (Version 2012, Geomagic, Inc., Morrisville, NC, USA), the model geometry was imported into the ANSYS (Version 14.0, ANSYS, Inc., Canonsburg, PA, USA) for further structural analysis. A simulated bone defect was placed on the right side of the mandible, including the condyle, coracoid process, and the upper part of the mandibular ramus. To achieve a satisfactory recovery of facial appearance, the defect section, with its accurate anatomical shape, was separated from the intact mandible model, and served as the design model (Fig. 1(b)) for the open-porous scaffold.

2.2. Design of the scaffold

The endoprosthesis consisted of two different parts: a load-bearing titanium alloy scaffold and bone graft materials, as shown in Fig. 2. The scaffold design was performed using the design model (Fig. 1(b)) to achieve an anatomically correct contour. A three-dimensional tetrahedral structure was applied to the open-porous scaffold, and two geometric parameters, the cell size and the strut diameter, were taken as design parameters. These geometric parameters were chosen according to the clinical situation and manufacturing limitations. For the SLM fabrication process, the thickness of each layer is approximately 100 μm [21]. Hence, to guarantee the quality of the fabricated scaffolds and the connectivity of the inner pores, the lower and upper limits of the strut diameter were set to 0.3 mm and 0.6 mm, respectively. An intermediate strut diameter of 0.45 mm was used as starting value for the initial scaffold, and the initial mean cell size was chosen to be 2.2 mm. Based on these initial parameters, the design model was decomposed into the approximately uniform and equilateral tetrahedral mesh by ANSYS software, then the initial tetrahedral structural scaffold, Fig. 3(a) and (b), was created along the mesh edges.

2.3. Finite element evaluation of the biomechanical behavior

To determine the mechanical properties of the initial scaffold under physiological loading conditions, a finite-element analysis was performed on the reconstructed mandible model (Fig. 2), which included the defective mandible and the initial scaffold filled with tissue-engineered bone graft implants.

To simplify the numerical simulations, all materials were considered isotropic, homogeneous and linear elastic. The scaffold was made of titanium alloy (Ti6Al4V) and fabricated by selective laser melting (SLM). The mechanical properties of the model were defined based on previously reported data [8,26–29] for dentin, cancellous bone, cortical bone, and titanium alloy. According to the research of Warnke, tissue-engineered bone graft implants had a similar stability to natural bone during loading [30]. Therefore, the properties of the regrown bone were assumed to be the same as those of cancellous bone. Table 1 lists the material properties used in this study.

The scaffold was precisely placed into the defect, and was assumed to remain fixed with respect to the residual mandible. Thus, no slipping was assumed along the bone/scaffold interface during loading. The regenerated tissues were assumed to fill the pores of the scaffolds, and remain bonded to the surrounding titanium alloy scaffolds. The top surfaces of the left condyle and the scaffold were fully restrained to prevent the rigid-body displacement of the mandible. The effect of the articular disk, which functions as a cushion between the condyle and temporal bone, was not considered in this study, and this condition has been implemented in other works [16,31].

The cortical bones, cancellous bones, dentin, and osteogenic material were meshed with 10-noded quadratic tetrahedral elements. Struts were implemented as structural beams with circular cross-sections. Each strut was meshed as a single beam element. The mesh of the reconstructed mandible model (Fig. 2), consisting of 266,337 elements and 336,837 nodes, was dense enough to ensure convergence of the numerical results.

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