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A custom-made temporomandibular joint prosthesis for fabrication by selective laser melting: Finite element analysis

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ABSTRACT

A novel and custom-made selective laser melting (SLM) 3D-printed alloplastic temporomandibular joint (TMJ) prosthesis is proposed. The titanium-6aluminium-4vanadium (Ti-6Al-4V) condyle component and ultra-high molecular weight polyethylene (UHMWPE) fossa component comprised the total alloplastic TMJ replacement prosthesis. For the condyle component, an optimized tetrahedral open-porous scaffold with combined connection structures, i.e. an inlay rod and an onlay plate, between the prosthesis and remaining mandible was designed. The trajectory of movement of the intact condyle was assessed via kinematic analysis to facilitate the design of the fossa component. The behaviours of the intact mandible and mandible with the prosthesis were compared. The biomechanical behaviour was analysed by assessing the stress distribution on the prosthesis and strain distribution on the mandible. After muscle force was applied, the magnitude of the compressive strain on the condyle neck of the mandible with the prosthesis was lower than that on the condyle neck of the intact mandible, with the exception of the area about the screws; additionally, the magnitude of the strain at the scaffold–bone interface was relatively high.

1. Introduction

The temporomandibular joint (TMJ) plays a unique and crucial role in our daily life, as it is involved in speech, expression and chewing. TMJ defects are caused by trauma, infection, tumour, ankylosis, and/or idiopathic resorption. Reconstruction of acquired TMJ defects is an obvious challenge in oral and maxillofacial surgery. Several techniques have been developed over the decades, such as costochondral grafting, iliac crest bone grafting, distraction osteotomy, fibular free flap, and alloplastic TMJ implants [1,2]. As compared to autogenous reconstruction, an alloplastic TMJ prosthesis can reduce donor site morbidity, provide immediate function, and be customizable. Although all of the currently available alloplastic TMJ implants have shown promise, artificial TMJs have not been accepted as universally as artificial hip and knee joints, as these were introduced several decades ago [3,4]. In addition to the biocompatibility problems that caused severe implant failures in the early 1980s [5], another main reason for concern has been the highly complex biomechanical role of the TMJ.

The TMJ is the point of articulation for the mandible, articular discs, and the base of the skull, which connects at the left and right joints. In order to adapt to different vital functions, mandibular condyles with incongruent surfaces carry out extremely complex movements with respect to the base of skull [6,7]. Accordingly, researchers have recommended the use of custom-made TMJ prostheses rather than stock prostheses, as custom-made TMJs can be better fitted to the anatomical structures of each individual to ensure correct physiological functioning [1,8–10].

Additive manufacturing techniques have been used recently for the construction of customized artificial TMJs. According to some studies [3,8,11], these products could improve the outcomes of artificial TMJ restoration. However, the design of the artificial fossa of the TMJ does not permit it to guide the movement of the artificial condyle along its physiological trajectory; thus, deviation of mandibular movement can occur, with the healthy contralateral TMJ suffering a secondary injury [9,12,13]. Moreover, currently available TMJ implants are all made of internally homogenized metal; therefore, the stiffness of the artificial condyle is much higher than that of condylar cortical and trabecular bone, which could readily induce a stress shielding effect subsequent to long-term usage [14,15].

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Several additive manufacturing techniques have recently been developed to fabricate structures for tissue engineering [16]. Among these approaches, selective laser melting (SLM) has been confirmed to be able to fabricate objects with precise internal architecture and external profiles. Several studies have shown that additive manufacturing of titanium alloy scaffolds can be used to repair bone defects because it has similar biomechanical properties [17–19]. A few researchers designed and fabricated a customized pure titanium condyle via selective laser melting technology in 2014 [20]. They designed a hollow structure for the condyle component by using two titanium plates to fix the prosthesis onto the outer surface of remaining mandible, an approach of fabricating the internal structure and connection design of the condyle component that differs from that of the present study. Considering these results, this technique may be suitable for the fabrication of a novel TMJ prosthesis.

A canine model was used in this study, as it has two left and right temporomandibular articular complexes, each of which comprises a condylomeniscal and meniscotemporal joint on either side, similar to the structure in humans. Both canine and human TMJs have a condylar joint and a reciprocally fitting one. The masseter, temporalis, and pterygoid muscles supporting the condylar processes within the fossa in canines are similar to those in humans. Canines also perform open–close and lateral movements of the mandible, despite their comparatively small range of lateral movement [21,22]. Several studies have been conducted on the TMJ using canine models, including temporomandibular joint meniscus reconstruction and unilateral condylectomy [23,24]. The ultimate goal of our research is to design TMJ prosthesis for humans. In this initial study, we obtained individual trajectories of condyle movement in the canine model and applied this information in the subsequent design of the articular surface of the TMJ fossa component. In a human study, we would use this same procedure to obtain the lower surface of the fossa component. Although the movement of the canine mandible differs from that of humans, the method with which we collected the envelope surface of condyle movement trajectory would be similar. As with the animal experiment, we will test the hypothesis that the custom-made prosthesis design can endure individual TMJ movement variations. If similar in vivo findings are achieved, the same procedure will be used to design TMJ prosthesis for humans by first obtaining individual trajectories of TMJ movement, and then by designing the customized articular surface.

Finite element analysis (FEA) is well established in the study of the biomechanical behaviour of the TMJ [25–28]. In this study, the individually designed TMJ prosthesis was constructed and tested using FEA. To reduce the stress shielding effect, the trabecular design in the novel TMJ prosthesis was optimized to be comparable to the structural modulus of bone. An inlay rod and an onlay plate were designed to strengthen the connection between the prosthesis and the remaining bone. To maintain healthy movement of the mandibular condyle, the articular surface of the prosthetic fossa component was designed with specific consideration for condylar movement. The reliability of the prosthesis was demonstrated by comparing the behaviour of an intact mandible and a mandible with the customized TMJ prosthesis.

2. Materials and methods

2.1. Computer-aided design (CAD) models

The bone structure morphology of the TMJ was constructed to accommodate an adult beagle canine. Computed tomography (CT) scans were performed using an 8-slice scanner (BrightSpeed, GE Medical Systems, USA) with a rotation time of 1 s, a slice thickness of 1.25 mm, voltage between 120 and 140 kV, and automatic exposure control. CT images were taken for four positions of the mandible: closed, 1/3-open, 2/3-open, and widest open positions.

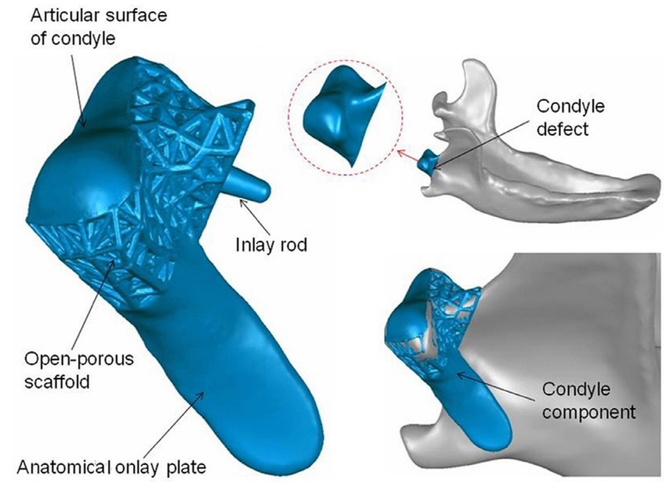

Fig. 1. Condyle component structure and design of the replacement prosthesis. Left panel: the profile of the condyle prosthesis; top right panel: the condyle defect region marked in blue in the intact mandible; lower right panel: the condyle defect region replaced by the condyle prosthesis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Design of the custom-made TMJ prosthesis

The individually designed TMJ implant was a total TMJ replacement prosthesis composed of condyle and fossa components, which were fixed to the mandible and zygoma separately with three screws and four screws, respectively. The prosthesis was installed on the right side of the mandible. Because of clinical experience and knowledge of the anatomy of a beagle skull, four screws were chosen to fix the fossa component to the cranium, and three screws were used to fix the condyle to the mandible. The screws used for the TMJ fixation were 2.0 mm in diameter, which is considered the minimum diameter able to provide sufficient stability [29]. The condyle component comprised titanium-6aluminium-4vanadium alloy (Ti-6Al-4 V), which was created using the Mlab Cusing 3D Metal Printing Machine (Concept Laser, Lichtenfels, Germany). The accuracy of the machine was approximately 40 μm. The fossa component consisted of ultra-high molecular weight polyethylene (UHMWPE), which was manufactured using a computerized numerical control machine (Dima Digital Machine, Shenzhen, China). The screws were also Ti-6Al-4 V alloy.

2.2.1. Design of the condyle component

The defect region of the mandible in this study included the entire condyloid process spanning from the mandibular notch to the posterior border of the mandibular ramus (Fig. 1). The condyle component of the TMJ prosthesis was designed to restore the condyle defect. The condyle component was designed as shown in Fig. 1. The profile of the condyle component was based on the anatomical shape of the condyle of the beagle model. Atop the condyle component was a preserved layer of 1-mm-thick condyle articular surface with a polished outer surface. This 1-mm-thick layer played an important role in load bearing and load transmission between the fossa and condyle components during mastication. The polished articular surface was purposed to decrease friction ratio and material wear. This layer was modelled as a solid entity in the FEA model; the friction ratio between the interface of the fossa component and condyle component was set to be 0.01.