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A novel dental implant abutment with micro-motion capability—Development and biomechanical evaluations

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ABSTRACT

Objective. The aim of this study was to develop a novel dental implant abutment with a micro-motion mechanism that imitates the biomechanical behavior of the periodontal ligament, with the goal of increasing the long-term survival rate of dental implants.
Methods. Computer-aided design software was used to design a novel dental implant abutment with an internal resilient component with a micro-motion capability. The feasibility of the novel system was investigated via finite element analysis. Then, a prototype of the novel dental implant abutment was fabricated, and the mechanical behavior was evaluated.
Results. The results of the mechanical tests and finite element analysis confirmed that the novel dental implant abutment possessed the anticipated micro-motion capability. Furthermore, the nonlinear force–displacement behavior apparent in this micro-motion mechanism imitated the movement of a human tooth. The slope of the force–displacement curve of the novel abutment was approximately 38.5 N/mm before the 0.02-mm displacement and approximately 430 N/mm after the 0.03-mm displacement.
Significance. The novel dental implant abutment with a micro-motion mechanism actually imitated the biomechanical behavior of a natural tooth and provided resilient function, sealing, a non-separation mechanism, and ease-of-use.

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1. Introduction

Dental implant systems are important for edentulous patients. With advancements in science and technology, dental implantation now has a high success rate of greater than 90% [1–5]. The success of the dental implant is mostly a result of implant stability [6–8], which is initially provided by threaded fixation and is supplied long-term by osseointegration. However, the notion that an ideal dental implant system is a completely firm structure (the alveolar bone, the fixture, the abutment, and the restoration) is controversial.

The biomechanical behavior of a natural tooth is provided by the periodontal ligament, with a capability for micro-motion of approximately 0.2 mm [9]. In addition, a natural tooth shifts rapidly toward the root at the initial stage of masticatory loading, and the adjacent teeth are compelled to jointly sustain this masticatory loading. The motion of the tooth gradually decreases as the masticatory load increases. When the masticatory load disappears, the tooth will return slowly to its initial position. This biomechanical behavior absorbs shock and disperses occlusal forces to protect the natural tooth and alveolar bone. Therefore, an ideal dental implant should provide stability as well as the micro-motion of a natural tooth. However, none of the current commercial dental implant systems provide micro-motion capability to imitate a natural tooth. The inconsistent movements between the dental implant and the natural tooth limit the design and success of an implant system [10–17].

Therefore, the aim of this study was to develop a novel dental implant abutment with a pericementum-like mechanism that can imitate the biomechanical behavior of a natural tooth. Such a novel dental implant abutment would not only maintain the primal success rate but also increase the long-term survival rate of the implant.

2. Materials and methods

This study was comprised of four main stages: preliminary design, finite element analysis (FEA), prototyping, and mechanical testing. First, a novel dental implant abutment with a micro-motion mechanism was designed. The special mechanism and the resilient component inside the abutment to provide micro-motion were created using the computer-aided design software SolidWorks (SolidWorks Corporation, Waltham, MA, USA). The geometry and motion modes of the novel dental implant abutment are schematically illustrated in Fig. 1. The novel dental implant abutment was devised for the fixture of a commercially available dental implant, but it can be easily modified to accommodate any dental implant fixture in the future. The outer contour of a commercial dental implant abutment was adopted to design the novel dental implant abutment. The novel dental implant abutment included the coping component, the resilient ring component, and the abutment component. The coping component was a partially cannular cylinder 4 mm in diameter and 7.5 mm in height with an inner thread. The dimension of the resilient ring component was a circular ring with an inner diameter of 2.8 mm, an external diameter of 4 mm, and a thickness of 0.4 mm. The abutment component was a cylinder 4.8 mm in diameter and 9.31 mm in height with outer threads for both the coping and the fixture as well as an annular fillister 0.6 mm in depth for the resilient ring component (Figs. 1 and 2a).

Second, a finite element (FE) model of the novel dental implant abutment was created using the commercial FE pre-processor HyperMesh (Altair Engineering, Inc., Troy, MI, USA). The three models for the coping, resilient ring, and abutment consisted of a total of 57,033 nodes and 293,128 four-node tetrahedral elements (Fig. 2b). All materials were assumed to be homogeneous and isotropic. Both the coping and abutment were assigned stainless steel material properties in the FE model. The Young's modulus and Poisson's ratio of the stainless steel were set to be 200 GPa and 0.3, respectively [18,19]. Moreover, the resilient ring was defined as silicone. The material properties of silicone were defined based on mechanical testing of the resilient ring. The stress–strain curve of the silicone ring was obtained from the force–displacement curve of a compression test of the fabricated prototype. The loading condition was simulated by applying a vertical force of 5 N and another force of 200 N on the top surface of the coping component. The bottom surface of the abutment component was constrained in all directions to simulate a rigidly clamped condition for the test specimen. The friction coefficient of all contact interfaces of the coping, resilient ring, and abutment were set to be frictionless in the FEA. Furthermore, the feasibility of the novel dental implant abutment was investigated. The FEA of the novel abutment was performed using the commercial software MSC. Marc Mentat (MSC Software, Los Angle, CA, USA). To ensure the numerical convergence of the model, the total strain energy error between different refined meshes was required to be smaller than 5% as the terminating criteria for mesh refinements. The model used for analysis fulfilled the convergence requirement. The FEA was performed, and the von Mises stresses and force–displacement curve were used to evaluate the mechanical behaviors of the novel abutment.

Third, a prototype of the novel dental implant abutment was fabricated. The materials used for the coping and abutment were 316L stainless steel, and the material used for the resilient ring was silicone (XIAMETER, Dow Corning, Midland, MI, USA). In addition, a rectangular block (15 mm in length, 15 mm in width, and 40 mm in height) with a fitting was fabricated to fix the test specimen. The bore of the clamping block, which was fabricated from 316L stainless steel was matched with the lower thread of the abutment. Finally, mechanical testing of the novel abutment was performed using an Instron universal testing machine (Model: 5544, Instron, Norwood, MA, USA). Moreover, a laser displacement sensor (Model: LB-1103, Keyence, Elmwood Park, NJ, USA) was incorporated to precisely measure the micro-motions. The laser beam was focused on the platen to measure the exact displacement of the micro-motion mechanism. The experimental setup of the mechanical test is shown in Fig. 3. The force control was set to 5 N with a loading rate of 0.1 N/s in the compression test. The sampling rates of the load cell and the laser displacement sensor were set to 10 Hz. The novel abutment was tested repeatedly nine times in the compression test. The force–displacement curve was obtained to evaluate the mechanical behavior of the novel abutment.