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Mode Superposition Transient Dynamic Analysis for Dental Implants with Stress-absorbing Elements: A Finite Element Analysis

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The purpose of this study was to analyze the dynamic behavior of a dental implant with a stress-absorbing element, using dynamic analysis. Two model types, stress-absorbing model with a resilient stress absorber made of polyoxymethylene and non-stress-absorbing model with rigid titanium, were employed. In both model types, the implant was 4.0 mm in diameter and 13.0 mm in length and placed in the mandibular first molar region. Shapes of the finite element implant and implant-bone were modeled using computer-aided design. All calculations for the dynamic analysis were performed using the finite element method. It was found that the stress-absorbing model had a lower natural frequency than the non-stress-absorbing model. In addition, the stress-absorbing model had a higher damping effect than the non-stress-absorbing model. It was concluded that mode superposition transient dynamic analysis is a useful technique for determining dynamic behavior around dental implants.

Key words : Transient dynamic analysis, Dental implants, Damping

INTRODUCTION

Titanium implants are widely used because of their advantageous mechanical properties and osseointegration[1−3]. Osseointegration of the titanium implant in bone is considered an essential criterion for a successful dental implant. However, compared with a natural tooth, a dental implant embedded in bone sometimes may be subjected to unacceptably high impact from occlusal forces. A dental implant and the surrounding bone are exposed to different stresses under occlusal forces due to the lack of a periodontal ligament around the dental implant[4]. Duyck *et al.*[5] reported that excessive dynamic loads caused crater-like defects lateral to osseointegrated implants. Therefore, stress analysis under impact loading may be helpful for predicting implant stability in oral functional conditions.

The finite element method (FEM) is a numerical method based on the principle of dividing a structure into a finite number of small elements that are connected with each other at corner points or nodes. It is a powerful tool for analyzing the distribution of stress. In particular, stress analyses of dental implants using FEM have been widely accepted by many researchers and published in many reports[6−8]. Generally, most stress analyses of dental implants using the FEM have been performed under static conditions. Despite the well-known static behavior of dental implants, a good understanding on the dynamic response of such dental implants is rather scarce.

A resonance frequency analysis of dental implants using impact loading has been used to assess dental implant-bone interfaces or the periodontal attachment level of natural teeth under dynamic conditions[9−11]. Implant vibration is induced using a transient force produced by an impact load. Elias *et al.*[9] reported that a frequency analysis technique, which was able to detect clinically relevant structural differences between interfaces, was able to distinguish these differences based on the type of bone at the interface and the degree of osseointegration between implant and interface. Huang *et al.*[10] reported that the boundary status of an implant can be monitored by detecting its natural frequency. Thus, a resonance frequency analysis can be used to investigate the dynamic behavior of a dental implant.

Dynamic analysis by FEM, mode superposition transient dynamic analysis, is employed for dynamic simulations in industrial fields[12,13]. This method uses natural frequencies and mode shapes from modal analysis to characterize the dynamic response of a structure in terms of transient excitations. Natural frequencies and mode shapes are therefore important parameters in the design of a structure for dynamic loading conditions, and are required to calculate the transient response.

It is suggested that a transient dynamic analysis of a dental implant may be a tool for predicting dynamic behavior, such as vibration, by impact loading. There have been a few reports related to dynamic analysis of stress within dental implants by FEM. Natali *et al.*[14] investigated the displacement amplitudes and frequencies of dental implants under vibration impact. Huang *et al.*[15] assessed the resonance frequency to determine the vibrating behavior of dental implants under a variety of surrounding bone conditions. The authors found that the resonance frequencies of dental implants were influenced by the type of bone around the implant, but they did not analyze the dynamic response of the implant or bone under impact loading. Thus far, the use of applied mode superposition transient dynamic analysis to predict the dynamic response in dental implants has not been performed.

One dental implant system with an internal stress-absorbing element has been commercially introduced[16−18]. Some investigators have attempted to analyze stress distribution around implants with an internal stress-absorbing element by using static FEM[19−21). However, there are conflicting opinions regarding the efficacy of an internal stress-absorbing element in a titanium dental implant system.

The model with an internal stress-absorbing element is well-suited for dynamic analysis. This is because it is predicted that the internal stress-absorbing element will have higher damping properties compared with other components, and mode superposition transient dynamic analysis may clarify the effects of the stress-absorbing element.

In the present study, the efficacy of an internal stress-absorbing element was evaluated using mode superposition transient dynamic analysis by comparing the model with and without the use of a resilient element. Computer-aided design software was used to develop three-dimensional (3D) models. In light of the role that mode superposition transient dynamic analysis played in this study, its usefulness in analyses of dynamic behavior around dental implants was thus confirmed.

MATERIALS AND METHODS

Two types of dental implant model were developed, with and without a stress-absorbing element. The IMZ TwinPlus Kinetic Line (Intra Mobile Zylinder, Friadent, Mannheim, Germany) implant system[16] was selected because this system has an option of using a stress-absorbing element. The investigation incorporated the planned simulation of the stress distribution functions of a tooth, the periodontium, and alveolar bone through the use of stress-absorbing elements called "intramobile connectors" (IMC), which are made of polyoxymethylene (POM)[22]. The stress-absorbing model consisted of a titanium implant, an IMC insert, an IMC, a superstructure, and a titanium retaining screw (Fig. 1a). The other dental implant model, without the internal stress-absorbing element, consisted of a titanium implant, a rigid titanium element, a superstructure, and a titanium retaining screw (Fig. 1b). In both model types, diameter of the implants was 4.0 mm and the length was 13.0 mm.

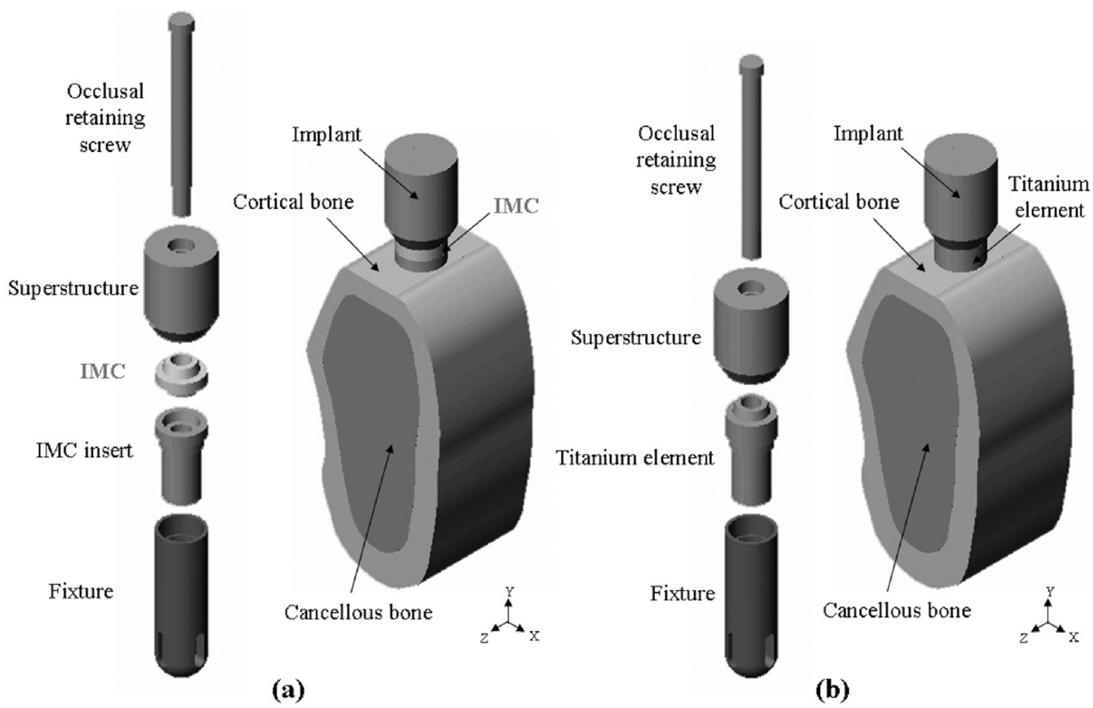

Fig. 1 Two types of dental implant system with diameter of 4.0 mm and length of 13.0 mm embedded in mandibular first molar region.
(a) Stress-absorbing model with resilient intramobile connector (IMC) made of polyoxymethylene;
(b) Non-stress-absorbing model with rigid titanium element.

Shapes of the finite element implant and implant-bone models were modeled using computer-aided design (CAD). The implant was embedded in the mandibular first molar site. The x-axis was set as the mesio-distal direction, the y-axis as the tooth axis direction, and the z-axis as the bucco-lingual direction. The bone model consisted of a cancellous bone core surrounded by a 2.0-mm thick cortical layer[8], which corresponded to Class 2 bone, according to the bone classification described by Lekholm and Zarb[23]. The CAD software was used for development of the 3D model (SolidWorks 2001 PLUS, SolidWorks Corp., Concord, Mass.). The CAD files were saved in Parasolid format, which enables file transfer to FEM software platform. The CAD model was imported into the FEM software, where it was meshed and the loads and constraints applied. All FEM calculations were performed with a software (ANSYS version 6.1, Cybernet Systems Co. Ltd., Tokyo, Japan). The CPU (Two Top, Tokyo, Japan) of the personal computer that was used had a speed of 500 MHz.

The FEM models are shown in Fig. 2. Analysis was performed using the 3D finite element method with four-node tetrahedral solid elements. The stress-absorbing model (Fig. 2a) was composed of 5,486 nodes and 27,972 elements, and the non-stress-absorbing model (Fig. 2b) was composed of 5,466 nodes and 27,860 elements. All materials were assumed to be homogeneous, isotropic, and having linear elasticity. In addition, interfaces between the materials were assumed to be continuous. The material properties used for FEM analysis were determined with a slight modification according to published literature[6,8,15,20,24] and are shown in Table 1.

Mode superposition transient dynamic analysis[12,13] is a method of using the natural frequencies and mode shapes from modal analysis to characterize the dynamic response of a structure in terms of transient excitations. The equation of motion was expressed as follows:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\} \tag{1}$$

where $[M]$, $[C]$, and $[K]$ denote the structural mass matrix, structural damping matrix, and structural stiffness matrix respectively, and where $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ denote the nodal acceleration vector, nodal velocity vector, and nodal displacement vector respectively. $\{F\}$ is the time-varying load vector given as follows:

$$\{F\}=\{F^n\}+s\{F^m\} \tag{2}$$

where $\{F^n\}$, s, and $\{F^m\}$ denote the time-varying nodal force, load vector scale factor, and load vector from the modal analysis respectively. $\{F^m\}$ is computed by performing a modal analysis.

The equation of motion of the modal coordinates was obtained as follows:

$$\{\ddot{q}\}+2\omega\xi\{\dot{q}\}+\omega^2\{q\}=\{F_q\} \tag{3}$$

where $\{q\}$, ω, and ξ denote the modal coordinates,

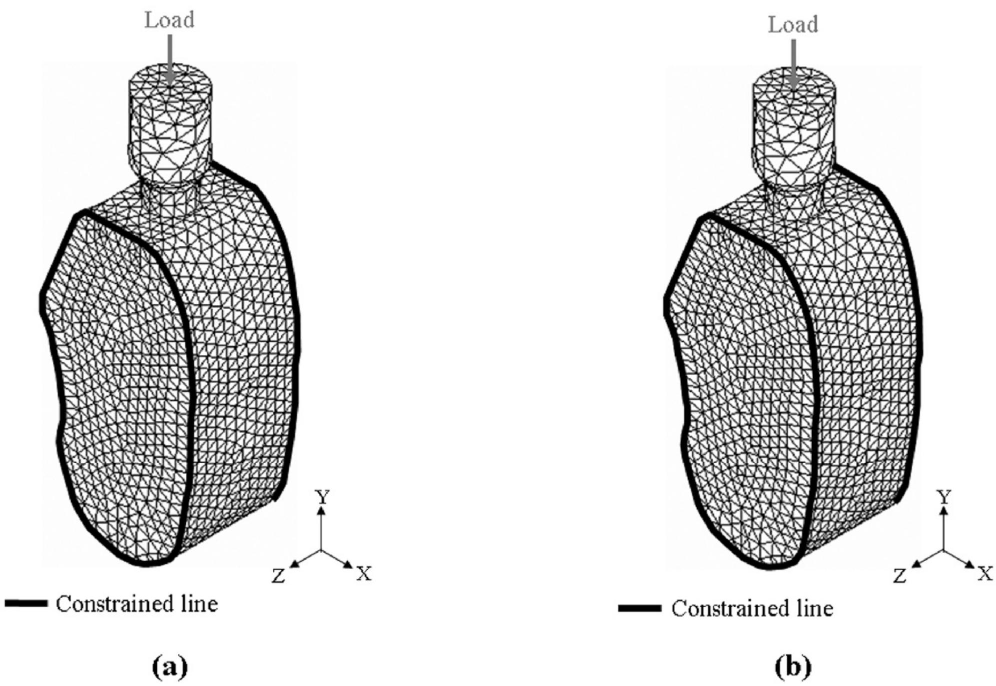

Fig. 2 Two types of finite element model of dental implant-bone. Each of these models consists of 4-node tetrahedral solid elements.
(a) Stress-absorbing model;
(b) Non-stress-absorbing model.

natural circular frequency of mode, and fraction of critical damping for mode respectively. First, a modal analysis was performed to obtain the vibration modes in this study. Generally, modal analysis is performed to determine the vibration characteristics such as natural frequencies and mode shapes. Here, the focus was on the vibration mode with deformation in the longitudinal direction. This is because when an impact load is loaded longitudinally at the implant, the longitudinal direction encounters the largest displacement. At the same time, the model was constrained in all directions by the line surrounding the cortical bone at the mesial and distal borders (Fig. 2).

The natural frequency and mode shape extracted from the modal solution were used to calculate transient response. In other words, the mode superposition method requires the mode shapes obtained from modal analysis to calculate the dynamic response. Then, the transient dynamic analysis carried out using the mode superposition method was used to determine the dynamic response of a structure under the action of any general time-dependent load.

The center of the occlusal surface at the top of the implant was impacted by a 100 N load, as shown in Fig. 3a. Damping property was calculated from the output at the bottom of the implant body in the natural frequency band of the vibration mode with deformation in the longitudinal direction. Fig. 3b is an example of the output recorded over time after an impact load. The measured damping property, usually called a logarithmic decrement, δ, was calculated by the following equation:

$$\delta = (1/n)\ln(a_m/a_{m+n}) \tag{4}$$

where a_{m+n} indicates the n^{th} maximum amplitude.

RESULTS

Fig. 4 shows the vibration modes of the models with and without the stress-absorbing element, obtained by mode superposition transient dynamic analysis. In both models, the deformed shape of distortion appeared at the cortical bone where the implant was attached. The influence of the IMC upon vibration mode could not be clearly confirmed. Fig. 5 shows the damping curve of the vibration mode of each model obtained by mode superposition transient dynamic analysis. In both models, the damping curves obtained were found to decrease over time. This meant that the vibration energy, which originated at the bone, dissipated over time. Further, the stress-

Table 1 Material properties used in this study

Material	Young's modulus (GPa)	Poisson's ratio (−)	Density (g/cm^3)	Loss factor (−)
Titanium	107	0.34	4.5	0.0003
IMC	3.45	0.35	1.4	0.1258
Cortical bone	13.7	0.30	2.0	0.0100
Cancellous bone	0.69	0.30	1.0	0.0381

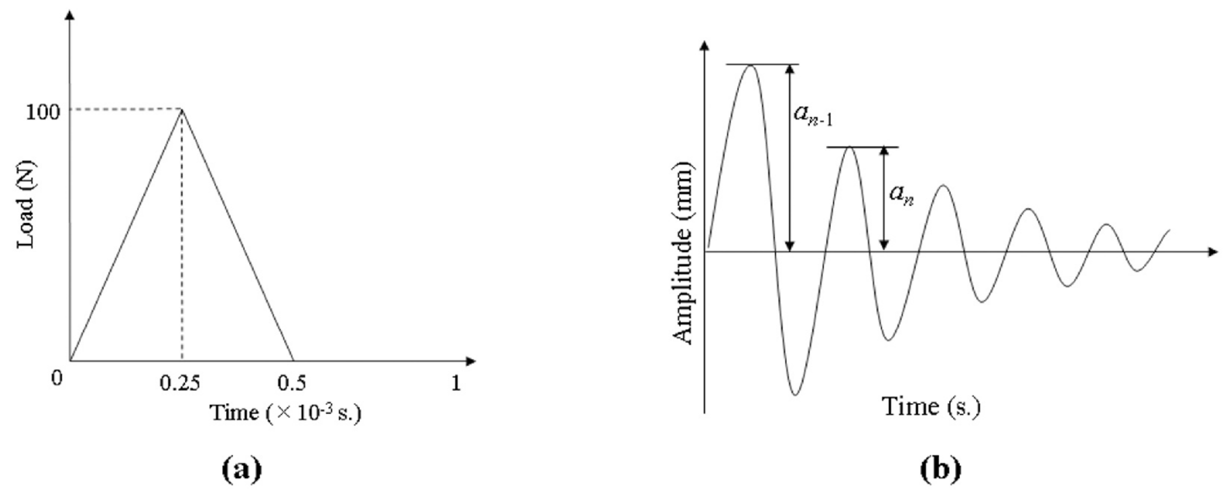

Fig. 3 Input and output in transient dynamic analysis.
(a) Application of impact load as input. Impact load applied at center of occlusal surface at top of implant;
(b) Example of damping curve as output. Damping curve showed displacement response at bottom of implant body following excitation in natural frequency band of first bending mode.

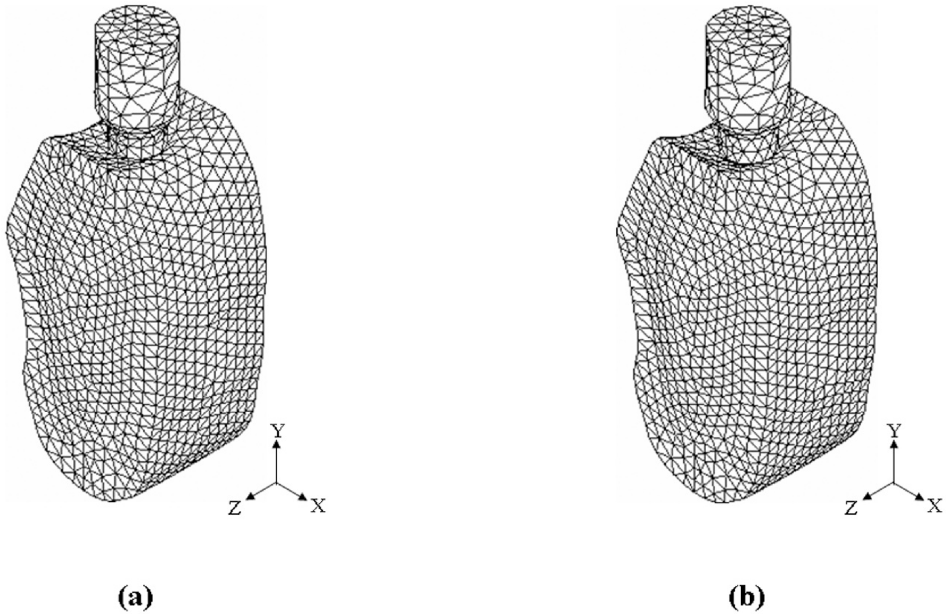

Fig. 4 Mode shapes of vibration mode.
(a) Stress-absorbing model;
(b) Non-stress-absorbing model.

Table 2 Vibration properties obtained by mode superposition transient dynamic analysis

Vibration property	Stress-absorbing model	Non-stress-absorbing model
Natural frequency (kHz)	24.75	25.24
Logarithmic decrement (−)	0.1343	0.1133

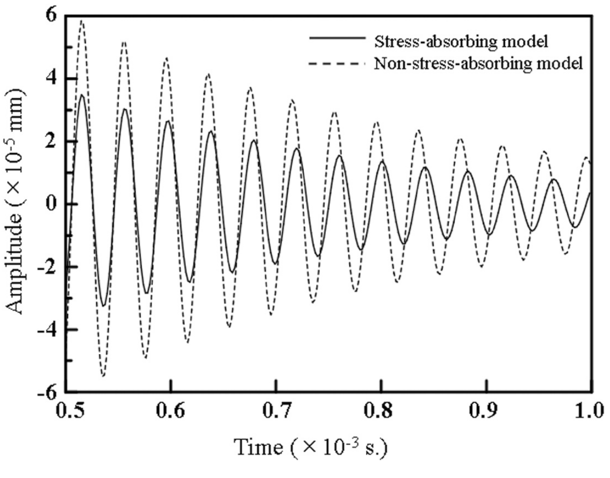

Fig. 5 Damping curves obtained by mode superposition transient dynamic analysis.

absorbing model showed amplitudes of lower magnitude in the damping curve caused by the impact load than did the non-stress-absorbing model.

Vibration properties such as natural frequency and logarithmic decrement — which was calculated according to Equation (4), are shown in Table 2. Natural frequencies of the stress-absorbing model and non-stress-absorbing model were 24.75 Hz and 25.24 Hz respectively. Logarithmic decrements of stress-absorbing model and non-stress-absorbing model were 0.1343 and 0.1133 respectively.

DISCUSSION

Every structure has its own natural frequency and logarithmic decrement or damping for each vibration mode. If the structure is subjected to excitation at its specific natural (resonant) frequency, input of a small amount of energy produces a rapid increase in the amplitude of the vibration of the structure. This increased amplitude may cause excessive stress, which may result in one or more structural fractures. In contrast, a damping effect in the structure sometimes restrains an increase in amplitude. Accordingly, vibration properties such as natural frequency and logarithmic decrement must be predicted to compare with the time-dependence of the actual loading.

In the present study, the effect of stress-absorbing elements of dental implants was analyzed by using the mode superposition transient dynamic

FEM which showed small differences in stress distribution in models with and without stress-absorbing elements.

Although many types of commercially available implant system are used in dental clinics, the IMZ system was selected in the present study because we could compare the effectiveness of the stress-absorbing element using implants with the same shape and dimensions.

Generally, natural frequency is an important parameter in the structure and is related to the rigidity and density of the vibrating object[15]. In the present study, a small difference existed in the natural frequency between the stress-absorbing and non-stress-absorbing models. This result stemmed from a difference in mechanical properties between the rigid titanium connector and the resilient IMC.

The logarithmic decrement/damping value of the stress-absorbing model was approximately 1.2 times higher than the non-stress-absorbing model. This result suggested that the stress-absorbing model dissipated more vibration energy than the non-stress-absorbing model. Damping property depends upon shear deformation of structure and is effective for stress distribution[25]. This implied that the internal IMC connector in the stress-absorbing model was more effective in stress distribution than the titanium connector in the non-stress-absorbing model. Thus, dental implants with stress-absorbing element can act as a damping structure which can reduce stress under dynamic impact loading. This is achieved by the incorporation of viscoelastic polyoxymethylene components[22] between the implant and the prosthesis, simulating the periodontal membrane and reducing the unfavorable effects of high stress at the implant-bone interface.

van Rossen *et al.*[19] investigated the stress distribution in bone around dental implants with and without stress-absorbing element under vertical static loading by using a two-dimensional FEM model. The authors suggested that if the modulus of the stress-absorbing element were the same as that of periodontal ligament, then the loading on the implant would have to be almost completely vertical. Thus, vertical loading was applied in the analysis in order to evaluate the effectiveness of the stress-absorbing element.

Although it may seem to be beneficial to incorporate the stress-absorbing element in dental prosthetic applications, it is not without its related potential complications. The IMC, composed of resilient polyoxymethylene, may not be durable for long-term use and a fractured apical fragment of the resilient intramobile element within the IMZ implant cylinder is difficult to remove[18]. Another potential approach would be the incorporation of an artificial periodontal ligament[26,27]. However, such an approach is currently unavailable.

The present study assumed that bone is a homogeneous and isotropic material with linear elasticity. These assumptions were made in order to compare the differences between two proposed implant designs. However, bone is a heterogeneous and anisotropic material; moreover, it does not exhibit linear elasticity but rather viscoelasticity. Thus, there were admittedly limitations to the current study. On this note, influences arising from the heterogeneity and viscoelasticity of bone in mode superposition transient dynamic analysis should be further investigated.

CONCLUSIONS

Within the limitations of the present study, it was found that the dynamic behavior of a dental implant system exhibited superior damping property by virtue of the stress-absorbing element. In light of this finding, mode superposition transient dynamic analysis appeared to be a useful technique for determining dynamic behavior around dental implants. It was thus expected that mode superposition transient dynamic analysis would likewise be useful for the analysis of dynamic behavior of other dental prostheses such as crowns and fixed partial dentures. Further, it might also be effective for the design of these dental prostheses to help prevent potential damage caused by impact loading. With so many areas of potential usefulness awaiting confirmation, it seemed warranted that future investigations should be undertaken to apply mode superposition transient dynamic analysis to determine dynamic behavior around dental prostheses such as crowns and fixed partial dentures.

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