Natural frequency assessment of stability of root keeper magnetic devices

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Abstract—*The aim of the study was to evaluate the potential for using natural frequency (NF) as an indicator for assessing the stability of a magnetic keeper device used in prosthodontic treatment. A three-dimensional finite element (FE) model of a root keeper–cement–dentine system was established for NF analysis. The model was first validated against a series of in vitro experiments. Then, NF values of the first vibrational mode of the FE model with various boundary conditions were calculated. The in vitro results showed that the measured NF values of the root keeper–incisor units decreased significantly ($p < 0.01$) from 9.07 ± 0.37 to 5.73 ± 0.10 kHz when the units were embedded in simulated bony tissue. Results obtained from FE simulations demonstrated that the root keeper would fully loosen when the constant values of the spring elements were lower than 10^4 N-m^{-1}. Furthermore, a linear increase in the NF values of the model was observed from 6.16 to 15.52 kHz, when the constant was increased from 10^4 to 10^7 N-m^{-1}, and the values then reached a plateau. The results indicate that the NF value of a root keeper has the potential to be used for monitoring the stability of such a device.*

Keywords—*Root keeper, Finite element method, Natural frequency, Stability*

Med. Biol. Eng. Comput., 2004, **42**, 388–393

1 Introduction

The two main areas where magnets are used in dentistry are orthodontics and prosthodontics (Blechman and Smiley, 1978; Springate and Sandler, 1991; Vardimon *et al.*, 1991; Riley *et al.*, 2001). However, the use of such magnetic materials in dental applications has been discontinued for a long time owing to their poor performance. Since the introduction of rare earth magnets such as Sm-Co and Nd-Fe-B alloys, it has become possible to produce magnets with small dimensions and strong attraction force for dental treatment (Moghadam and Scandrett, 1979; Laird *et al.*, 1981; Gilling, 1981; 1983; Pezzoli *et al.*, 1986; Highton *et al.*, 1986; Riley *et al.*, 2001).

Recently, a novel matgnetic device, a root keeper, was introduced for dental prosthetic treatment. In this system, a prefabricated post with a magnetic keeper is cemented directly into the canal of an endodontically treated root; thus the casting procedure can be omitted, and additional tooth structure can be preserved.

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Paper received 23 July 2003 and in final form 26 February 2004

MBEC online number: 20043896

Investigations into the main problems with such magnetic devices have mainly focused on the attractive force, corrosion of magnetic alloys and loosening problems of the interface between the post and its surrounding materials (Funda and Gülsen, 1995; Gillings and Samant, 1990; Angelini *et al.*, 1991; Bondmark *et al.*, 1994; Riley *et al.*, 1999). Although numerous methods, such as dyeing, isotopes, micro-organism, electrochemistry and osmotic pressure, have been used for detecting interface problems of traditional post and core devices (Perez Moll *et al.*, 1978; Sorensen and Engelman, 1990; Isidor and Brondum, 1992) and for assessing the interface problems of root keepers, they are not suitable for long-term follow-up or early diagnosis *in vivo*.

The natural frequency of a structure is a function of its mass and stiffness (Thomson, 1988). Physically, it can reflect variations in mass, stiffness and boundary conditions when the material properties change. Because it can be used for quantitative analysis and is non-intrusive and non-destructive, it is also used in assessing interface problems of dental implants (Meredith *et al.*, 1996; 1997*a*; Huang *et al.*, 2001*a*; 2002). For dental material applications, the natural frequency has proven to be a useful parameter for determining the mechanical properties of dental ceramic and resin-based materials (Meredith, 1999; Fischer *et al.*, 2001). Owing to the lack of an adequate detection technique to assess the stability of root keeper devices, the potential for using NF as an indicator for detecting the stability of a root keeper was evaluated in this study.

2 Materials and methods

2.1 *Instrumentation and testing methods*

To understand the effects of surrounding materials on the NF values of a root keeper, devices were tested through a series of *in vitro* model experiments. During the tests, a transient force was directly applied to the top surface of the keeper with an impulse force hammer* to cause the root keeper to vibrate (see Fig. 1). The vibrational responses of the device were acquired through a piezo-electric microphone sensor†. Both the impulse force and the induced vibration response signals were transferred to a personal computer though a two-channel dynamic signal analyser interface card‡.

Fast Fourier transformation (FFT) was calculated using commercial analysis software** to translate the response signal spectrum from a time domain to a frequency domain. One final NF for each test was obtained by averaging the results from five samples. In addition, one-way analysis of variance (ANOVA) was applied to test the statistical significance of differences between NF values and the surrounding conditions of the root keepers.

2.2 *In vitro modal testing experiments*

Tested samples were divided into three groups. In group 1, the root keepers were clamped directly by a clamp stand. The NF values of the test specimens were recorded with clamping forces of from 30 to 150 N-mm in steps of 30 N-mm (Fig. 2*a*). In group 2, root keepers were placed into upper central incisors and fixed with resin cement. The root keeper–incisor units were pretreated endodontically and sealed with gutta-percha at the apex. Before testing, these samples were fixed to the clamping stand with a force of 150 N-mm (Fig. 2*b*). In group 3, samples were pre-treated identically to specimens in group 2 and then were embedded in white stone blocks with dimensions of $10 \times 10 \times 15\,\text{mm}^3$. The root keeper-supporting tooth–stone block specimens were also clamped with a clamping force of 150 N-mm (Fig. 2*c*).

2.3 *Finite element modelling*

To determine the effects of different boundary conditions on the NF values of a root keeper, a 3D FE model (Fig. 3), containing root keeper, resin-cement, gutta-percha, supporting teeth with endodontic treatment, periodontal membrane, compact bone and spongy bone, was built using an FE software package††. The geometry and dimensions of these structures, including the 25 μm thickness of the cement, the cone-like supporting teeth, the 0.25 mm thickness of the periodontal membrane and the 5 mm length of the gutta-percha were selected according to previous studies (SHILLINGBURG *et al.*, 1997; LEE *et al.*, 2000). The alveolar process was located 2–3 mm apically from the cemento-enamel junction (SHILLINGBURG *et al.*, 1997).

Because the first vibrational mode of the human mandible is a bending vibration along a lingual–buccal direction (LEE *et al.*, 2003), the boundary conditions of our model were chosen to fix the mesial-distal side of the bone at all nodes (LEE *et al.*, 2000).

*Model GK291C80, PCB Piezotronics, Buffalo, NY, USA.
†FM-10B, FC Electronics, Taipei, Taiwan.
‡AD102A, Prowave Engineering, Hsinchu, Taiwan.
**SD200N Signal Doctor, Prowave Engineering.
††ANSYS, Swanson Analysis Systems, Houston, PA, USA.

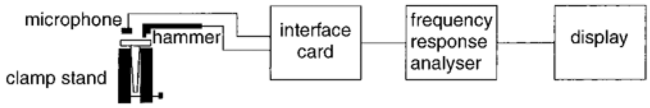

Fig. 1 *Schematic diagram of modal testing experiment*

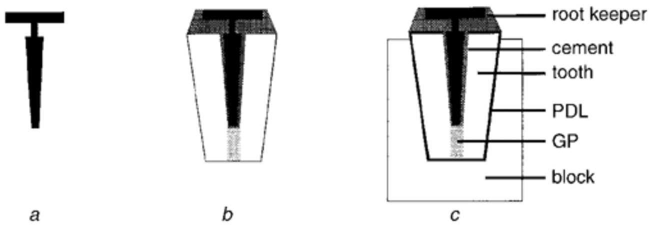

Fig. 2 *Natural frequency test for three root-keeper systems. (a) Root keeper only. (b) Root keeper placed in tooth. (c) Root keeper–tooth system embedded in stone block*

The entire model consisted of 4586 nodes and 3996 elements. The mechanical properties of the model were assumed to be homogeneous, isotropic and linearly elastic. The specific values of the properties were adopted from previous studies and are listed in Table 1 (CRAIG, 1980; KHERA *et al.*, 1988; HIROKO *et al.*, 1993; HO *et al.*, 1994; KROSCHWITZ and HOWE-GRANT, 1994; PARK, 1995; LEE *et al.*, 2000). The model was used to simulate the modal tests of the *in vitro* experiments. The first mode of natural frequencies and vibrational mode shapes of the FE model with various boundary conditions were calculated.

Interfaces between the root keeper and the resin cement were connected by spring contact elements. Because the exact constant values of these interface elements were difficult to measure directly, the elastic constants were altered with in a large range from 10^{-3} to $10^{9}\,\text{N-m}^{-1}$. The NF value of the root keeper with totally loosened boundary can be determined by checking whether rigid-body vibrational modes exist. On the other hand, the NF value of the root keeper with firm constraint can be decided by checking whether the NF value is at plateau. We validated, the FE model by checking whether the NF value of the model at plateau was close to the corresponding data obtained from modal testing experiments or not.

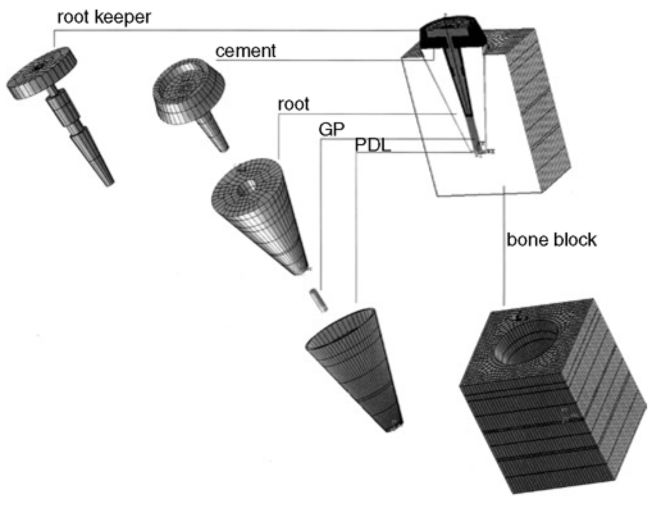

Fig. 3 *Three-dimensional finite element model established in this study*

Table 1 Mechanical properties of the finite element model

	Young's modulus, Gpa	Density, g ml^{-1}	Possion's ratio
Dentin	18.6 (HO *et al.*, 1994)	2.2 (CRAIG, 1980)	0.31 (KHERA *et al.*, 1988)
PDL	0.05 (LEE *et al.*, 2000)	1.1 (LEE *et al.*, 2000)	0.45 (KHERA *et al.*, 1988)
Alveolar bone	3.5 (KHERA *et al.*, 1988)	1.3 (HIROKO *et al.*, 1993)	0.33 (KHERA *et al.*, 1988)
Gutta-percha	0.69 MPa (HO *et al.*, 1994)	0.96 (KROSCHWITZ and HOWE-GRANT, 1994)	0.45 (HO *et al.*, 1994)
Composite resin	8.3 (HO *et al.*, 1994)	2.0 (CRAIG, 1980)	0.28 (HO *et al.*, 1994)
Stainless steel	200 (HO *et al.*, 1994)	7.9 (PARK, 1995)	0.33 (HO *et al.*, 1994)

3 Results

In the *in vitro* tests, samples in group 1 that were directly clamped to the clamp stand with a force of 30 N-mm showed the lowest NF values of 12.39 ± 0.03 kHz. When the clamping force rose from 30 to 90 N-mm, measured NF values increased linearly ($R^2 = 0.9993, p < 0.01$) to 13.85 ± 0.17 kHz. As shown in Fig. 4, the measured natural frequency did not change significantly when clamping forces exceeded 90 N-mm. The average NF values of the samples in groups 2 and 3 were 9.07 ± 0.37 and 5.73 ± 0.10 kHz, respectively. As shown in Fig. 5, the measured values demonstrated significant differences among the three groups for each clamping force ($p < 0.01$).

In finite element simulations, when the k value of the spring contact elements changed from 10^{-3} to 10^3 N-m^{-1}, the first six vibration modes were rigid body motions along different directions. For the given k values, the first bending vibration was found at the seventh vibrational mode (Fig. 6). The NF values of the first six vibrational modes were much less than that of the seventh bending mode. This phenomenon indicates that the boundary of the root keeper system was beginning to loosen when the k values were set to less than 10^4 N-m^{-1}. Therefore root keeper models with k values of less than 10^4 N-m^{-1} were not analysed or discussed in the latter investigation. When the k values of the spring contact elements were set to between 10^4 N-m^{-1} and 10^7 N-m^{-1}, the first vibrational mode was a bending vibration. The calculated NF value of the model was 6.16 kHz, with a k value of 10^4 N-m^{-1}, and increased linearly to

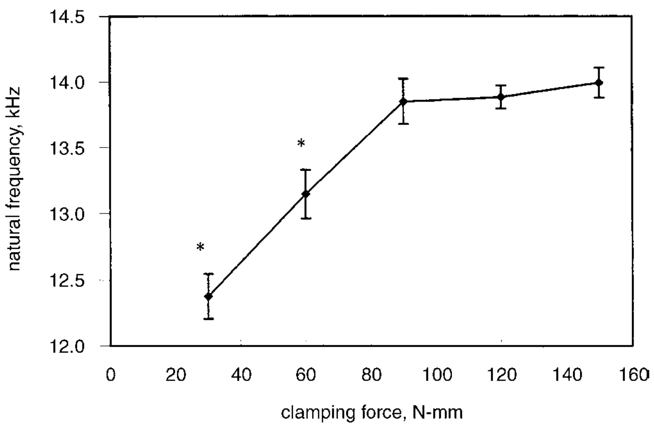

Fig. 4 *NF values of root keeper under various clamping forces in first in vitro test group. Data are presented a mean ± SD. (*) Significant difference (p < 0.01)*

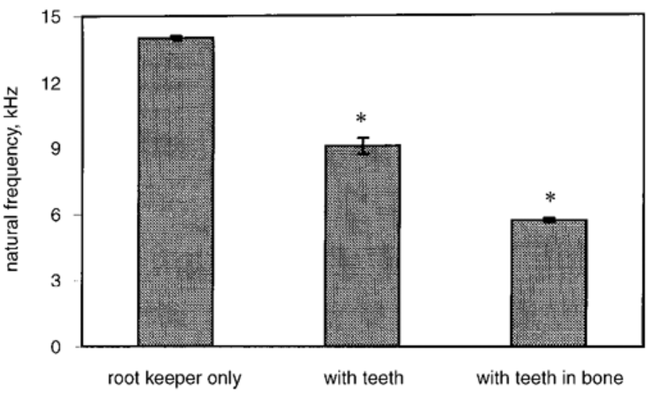

Fig. 5 *NF values of root keeper models with various surrounding tissues. Data are presented as mean ± SD. (*) Significant difference (p < 0.01)*

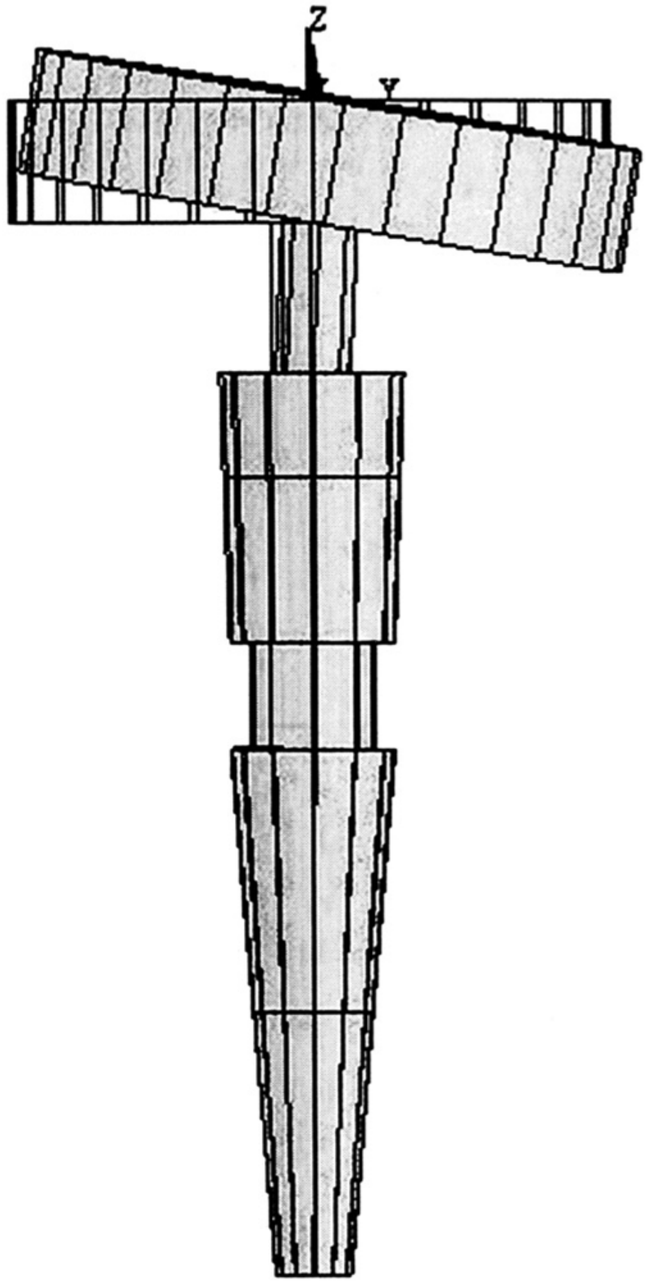

Fig. 6 *First bending mode shape of root keeper*

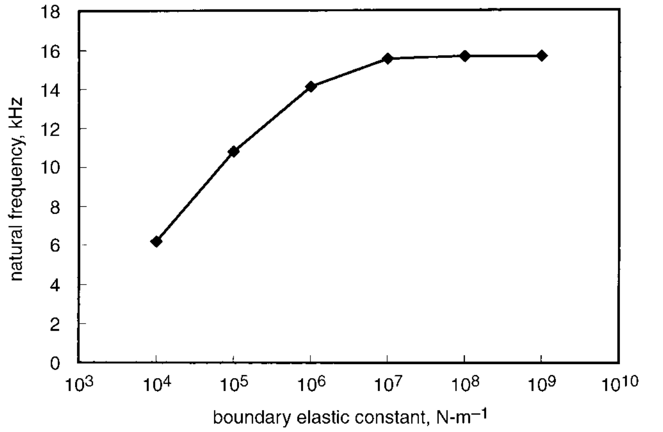

Fig. 7 *Natural frequencies calculated by FE model with various k values*

15.52 kHz when the k value was set to 10^7 N-m^{-1}. After k values of the model exceeded 10^7 N-m^{-1}, the NF value of the model reached a plateau (Fig. 7).

4 Discussion

In industrial applications, NF analysis is a traditional, non-destructive method for material testing. Recently, several scholars have also tried using such techniques to analyse interface problems of implants and mechanical properties of tissues in orthopaedics. However, owing to problems associated with the covering of soft tissues, clinical utilisation of such techniques was restricted (NOKES, 1999; LOWET, 1993; LOWET *et al.*, 1996). Because teeth in the oral cavity are exposed without a soft tissue covering, this facilitates the use of such techniques for analysing the stability of teeth and associated dental materials (WILLIAMS and WILLIAMS, 1997; LEE *et al.*, 2000; HUANG *et al.*, 2001*b*; 2002; MEREDITH *et al.*, 1997*a*;*b*).

A root keeper is a beam-like structure. From the elementary theory of beams (also known as the Euler–Bernoulli theory), the equation of motion for the free vibration of such a uniform beam can be expressed as follows:

$$EI\frac{\partial^4 w}{\partial x^4}(x,t) + \rho A\frac{\partial^2 w}{\partial t^2}(x,t) = 0 \qquad (1)$$

where E is Young's modulus, I is the moment of inertia, ρ is the mass density, A is the cross-sectional area of the beam, and $w(x, t)$ is the lateral displacement. When an end of the beam is connected to a linear spring, the resisting force is balanced by the shear force at the end. Thus

$$\frac{\partial}{\partial x}\left(EI\frac{\partial^2 w}{\partial x^2}\right) = \pm\left(kw + m\frac{\partial^2 w}{\partial t^2}\right) \qquad (2)$$

where k is the spring constant. In addition, the bending moment must be zero; hence,

$$EI\frac{\partial^2 w}{\partial x^2} = 0 \qquad (3)$$

As (2) and (3) are the boundary conditions of (1), the natural frequency of such a beam must be affected by the boundary spring constant k.

From the above equation, the natural frequency f of a root keeper can be solved as follows:

$$f = \alpha\sqrt{\frac{EI}{\rho A l^4}} = \alpha\sqrt{\frac{EI}{\rho' l^4}} \qquad (4)$$

where l is the effective vibrating length of the beam, ρ' is the mass per unit length, and α is a constant related to the boundary conditions (THOMSON, 1988). From (1)–(3), if springs were used to connect the end of a beam, the α value of the beam must be correlated to the spring constant k.

To obtain the vibration signal of the device, specimens were tested with a vertical percussion direction. KAY *et al.* (1998) also used a similar technique to detect NF values of an external fixation device *in vivo*. Their results also showed that the NF values of a pin-like device implanted in hard tissue could be detected by vertical excitation and detection (KAY *et al.*, 1998). As shown in Fig. 4, when root keeper devices were directly clamped, the measured NF values increased as the clamping force was changed from 30 to 90 N-mm. This is because the calculated NF value increased following the increasing α value. The measured NF values did not change significantly when the clamping force exceeded 90 N-mm. This means that the device had reached a stable state, and the α value did not change further. Clinically, the stability of the root keeper system increased as the cement gradually set. After the cement had completely set, stability of the root keeper system was achieved, and therefore the NF value reached a plateau. In summary, the phenomenon of the cement-setting process could be detected through changes in the NF values.

In realistic situations, a root keeper would not stand alone. To understand the effects of cement, root and bony tissue on the measured NF values of the root keeper system, NF values of the tested specimens were measured when the devices were embedded in various surrounding materials, as shown in Figs 2*b* and *c*. The results plotted in Fig. 5 show that the boundary materials can affect the measured NF values. This is because the boundary materials can increase the entire mass of the test system. According to (4), it is apparent that an increase in the value of ρ' will lead to a decrease in the NF value of the samples. Although the measured NF values must be lower than the real value when there is material surrounding the root keeper, results obtained from numerical approaches (Fig. 7) show that the NF value of a root keeper can reflect the degree of boundary strength.

In this study, both *in vitro* modal testing experiments and FE modelling were performed to test the effects of boundary strength on the NF values of a root keeper. Although the parameters carried out for boundary condition simulations are different in the two methods (clamping force for modal tests, and boundary elastic constant for FE simulations), we can determine the NF values of the root keepers with firm constraints by identifying the data points at plateau in Figs 4 and 7. Furthermore, there should exist correlations between the two independent variables. For example, an FE model with a higher boundary elastic constant can represent the experiment model with a higher boundary constraint, and *vice versa*.

However, we do not try to reach a conclusion on how the two parameters are exactly related, owing to the limited data we obtained. In this study, only the NF value was used as a parameter for discussion. Therefore, although we cannot provide the exact relationship between the variables, the validation results of the FE model will not change. Comparison of the data plotted in Figs 4 and 7 revealed similar NF results at plateau. As well as the curves of the two plots being similar in shape, the NF value of the root keeper with a stable boundary condition obtained from the numerical approach (15.52 kHz) is close to the corresponding result of the modal testing experiment (13.85 ± 0.17 kHz). This demonstrates that the model used in this study is a credible model for natural frequency analysis.

In our numerical simulation, all materials were considered isotropic, homogeneous and linearly elastic. Therefore the contact spring elements physically followed the Hooks' principle. By giving various k values to the spring contact elements, the model is capable of effectively simulating the degree of tightness between the root keeper and the cement. In vibration analysis, the vibrational mode shape is also an important parameter when the structural characteristics of test specimens are being assessed. When the k value of the contact elements in the model was set between 10^{-3} and 10^{3} N-m^{-1}, the first six vibration modes were rigid body motions, with a vibrational frequency far lower than the NF values of the first bending vibration. This phenomenon fits the vibrational characteristics of an unrestrained structure (RAO, 1999). Therefore the root keeper system totally loosened when the k value fell into the above range.

However, when the k value was increased from 10^4 to 10^7 N-m^{-1}, the NF value of the first bending mode increased. This was because the stability of the root keeper system increased. In contrast, if the interface between the root keeper and the surrounding material was damaged (e.g. through dissolution or fatigue), the stability of the system would decrease. In this situation, the NF values of the device would consequently diminish. Therefore, for physical analysis, the boundary strength between a root keeper and its surrounding cement can be simulated by a pseudo spring with k values of 10^4–10^7 N-m^{-1}, depending on the degree of tightness. On the other hand, as demonstrated in Fig. 6, the first vibrational mode of the root keeper system calculated by the finite element model was a bending vibration at the interface between the keeper and the post portion. This means that the interface is a weak point of the structure. This point fits clinical observations well.

In conclusion, our limited results demonstrate that, although a more advanced study is needed in the future, NF values can be used as a useful parameter for assessing the stability of a root keeper device. On the other hand, the method presented in this study can serve as a reference for developing a non-destructive and non-invasive testing device in other pin-like implanted devices.

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