Original Article

Effect of loaded orthodontic miniscrew implant on compressive stresses in adjacent periodontal ligament

Mhd Hassan Albogha[a]; Ichiro Takahashi[b]

ABSTRACT

Objectives: To describe the relationship between the proximity of miniscrew implants (MSIs) to the periodontal ligament (PDL) and stress in the PDL under different load magnitudes and different bone properties.

Materials and Methods: Sixteen subject-specific finite element models of the region of the maxillary first molar and second premolar were developed using computed tomography images of four patients. For each patient, an MSI surface model derived from micro-computed tomography was placed at four different distances from the premolar PDL. Finite element analysis was conducted with mesial load on the MSI, increasing from 1 N to 4 N. Peak absolute compression stress (CS) was calculated at each 1 N step. Stepwise multiple regression modeling was conducted to explain compressive stress by proximity, load magnitude, and bone properties.

Results: The multiple regression model explained 83.47% of the variation of CS and included all three factors: proximity, load magnitude, and bone properties. The model expected significant interaction between the bone properties and load magnitude, implying that strong bone properties could be associated with significant increases in CS at small increases in load.

Conclusions: To ensure the safety of adjacent roots, MSIs should be placed at least 1 mm from the roots. Assessment of alveolar bone properties is recommended when the use of MSI is intended, as some patients may present with strong bone properties and thereby a high risk of MSI-induced root resorption. (*Angle Orthod.* 2019;89:235–241.)

KEY WORDS: Orthodontic mini-implant; Periodontium; Finite element; root resorption

INTRODUCTION

Orthodontic miniscrew implants (MSIs) are now commonly used in orthodontic clinical practice as temporary anchorage devices. Various orthodontic treatments and tooth movements have become effectively achievable with minimum or no loss in anchorage.[1] Although MSIs show remarkable efficiency and sufficient stability, several risks and complications may accompany their use.[2] The most common complication is the inadvertent injury of adjacent periodontal ligaments (PDLs) or dental roots. Injury of the PDL may induce extensive root resorption, especially if the MSI is not removed immediately.[3–5] On the other hand, Lee et al.[6] demonstrated that an MSI in proximity to adjacent PDLs may induce root resorption even if the MSI is not directly interfering with the root or PDL. A possible reason for this phenomena could be the compressive stresses transferred to the PDL, whose cells play a significant role in regulating the formation of osteoclasts by producing chemical signals in response to mechanical stress.[7–9] Previous in vitro studies found that PDL cells under compressive stresses of the order of 0.5 g/cm^2 could show overexpression of chemical signals that mediate root resorption.[10–12] Until now, there has been no attempt to measure or quantify compressive stresses in the PDL adjacent to MSIs. Measuring these stresses would improve our

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Accepted: July 2018. Submitted: December 2017.
Published Online: September 19, 2018

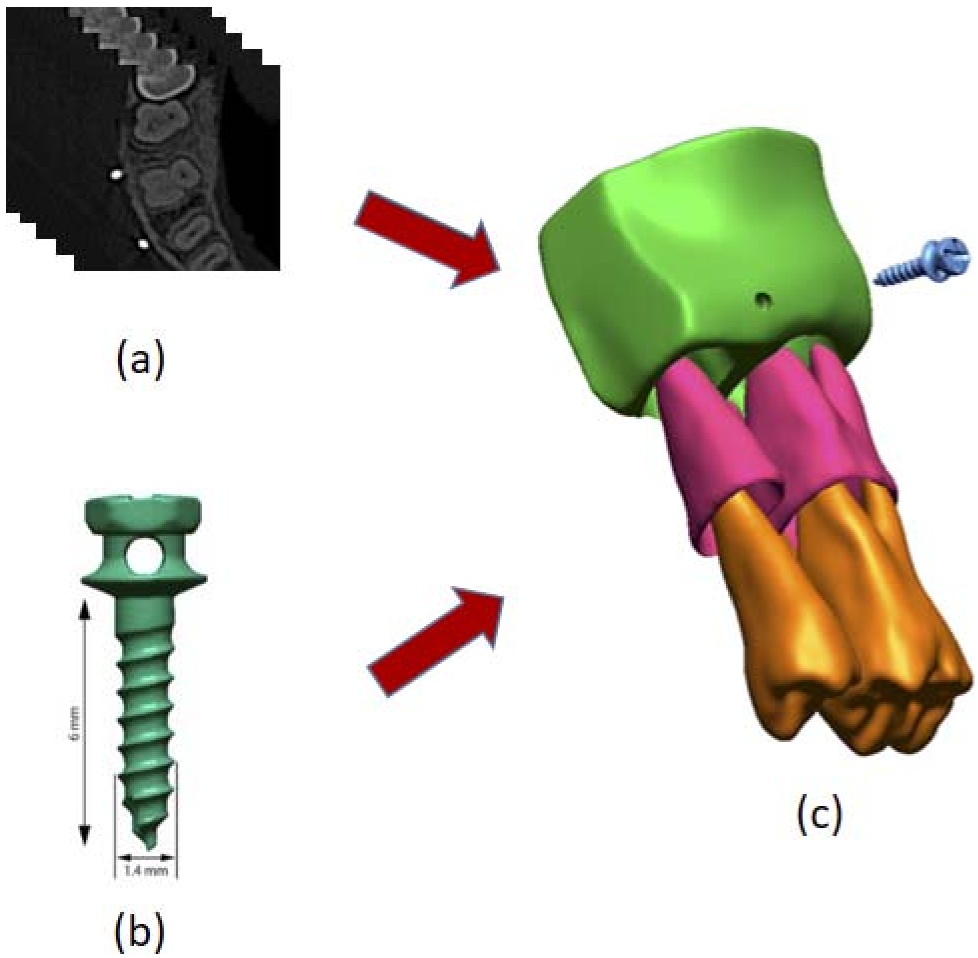

Figure 1. A computed tomography image of a patient (a) and micro-computed tomography image of the miniscrew implant (b) are used to construct a three-dimensional model (c) for analysis by the Finite element technique.

understanding of the effect of MSIs on the adjacent PDL and thereby improve clinical application of MSIs.

Practically, it is not possible to measure the stresses in the PDL in vivo directly. The finite element method could be a reliable and noninvasive technique to measure stresses in the PDL. Recent advances in computational technology allow finite element simulations of bone specimens to be very close to reality by constructing finite element models based on specimen-specific geometries and properties.[13] In this technique, a computed tomography (CT) image of the patient is obtained and used to produce patient-specific finite element models that have patient-specific bone geometry and CT-voxel-based bone mechanical properties. Until now, no previous study has used this technique to measure stress in the PDL in the vicinity of MSIs. The current study used this technique to describe the changes in compressive stress in the PDL in relation to the proximity of a miniscrew to the PDL under varying loading magnitudes.

MATERIALS AND METHODS

This retrospective study was approved by the ethics committee of Kyushu University Faculty of Dental Science (No. 25-279). CT scans of four female patients (mean $\pm$ standard deviation age $=$ 20.7 $\pm$ 4.3 years) were used to develop patient-specific finite element models (Figure 1). The CT images were of 0.214-mm pixel size and 0.5-mm slice thickness. All images were obtained with Aquilion TSX-101A (Toshiba Medical, Tokyo, Japan) at 120 kVp and 150 mA. None of the patients had a systemic disease or syndrome. For each patient, one side only (right or left) was used to develop the finite element model. The side with greater interradicular width between the roots of the maxillary first molar and second premolar was chosen. The mean and standard deviation for IRW was 4.3 $\pm$ 0.5 mm. Each of the CT images was used to construct a three-dimensional (3D) model of the anatomical segment consisting of the maxillary first molar, second premolar, their own PDLs, and surrounding bone.

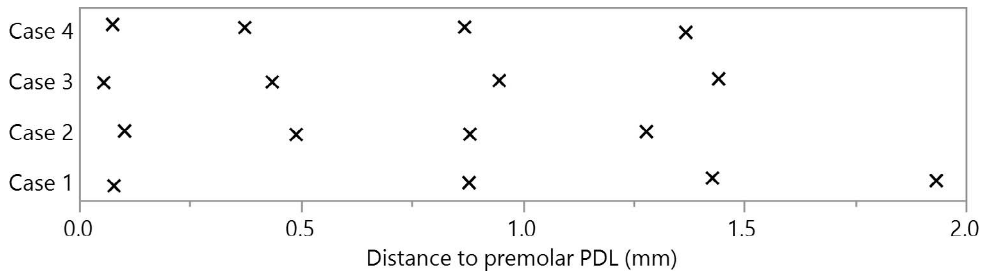

Figure 2. In four patients, the miniscrew implant three-dimensional model was combined with the final model at four different distances from the periodontal ligament of the maxillary second premolar.

A 3D surface model of a miniscrew was constructed using a micro=CT image of a DualTop MSI (Jeil Medical Corporation, Seoul, Korea). The miniscrew was 6 mm long and 1.4 mm in diameter. The miniscrew 3D model was integrated into each of the anatomical segments' 3D models at four distances from the premolar PDL (Figure 2). The 16 resultant 3D models were analyzed using the finite element method.

Each of the 16 models was discretized with tetrahedral elements in ANSYS version 15 (Ansys Japan KK, Tokyo, Japan) and consisted of roughly 600,000 elements and 120,000 nodes. The elastic modulus for each element of bone was calculated from the CT image using a protocol detailed in a previous study.[14] Average peak elastic modulus for peri-screw bone (E_b) was 16 $\pm$ 1.6 GPa. The Poisson ratio was considered to be 0.3 for bony elements. Elastic modulus (E) and Poisson ratio (ν) for other components in the model were as follows: PDL, E = 0.044 MPa, $\nu = 0.45$; teeth, E = 20.7 GPa, $\nu = 0.45$; and MSI, E = 114 GPa, $\nu = 0.34$.[15,16] Load was applied on the head of the MSI in a mesial and horizontal direction. The nodes on cutting faces of the bone segment were fixed in all directions (zero degrees of freedom) (Figure 3). The finite element models were solved in MechanicalFinder version 6.1 (RCCM Inc, Osaka, Japan) using linear elasticity theory for small displacements. Then, the absolute peak compressive stress (CS) in the premolar PDL was calculated at four loading magnitudes (1, 2, 3, 4 N). In total, 64 calculations of CS were obtained.

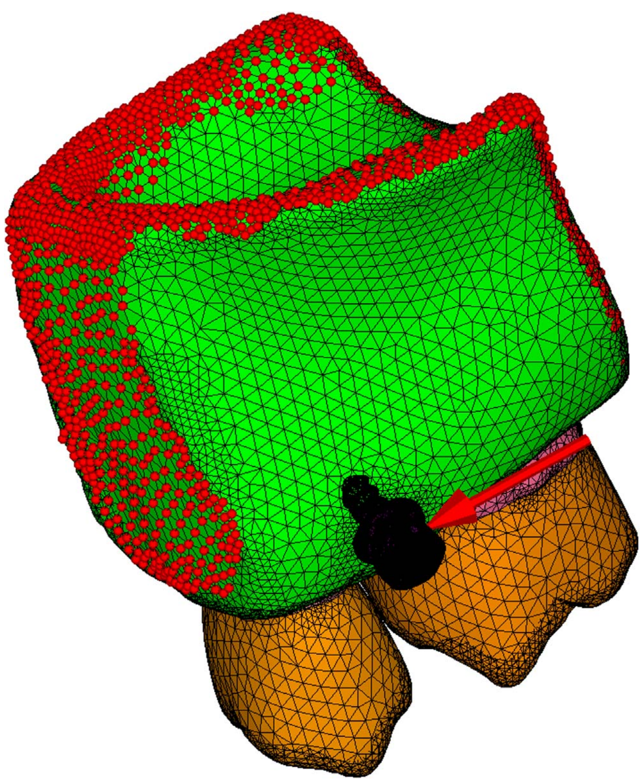

Figure 3. The final model discretized with load on the miniscrew implant head (the arrow) and constraints on the cutting faces of bone (nodes with spheres).

Stepwise multiple regression modeling was conducted to explain CS in the PDL by proximity of the screw to the PDL, loading magnitude and peak elastic modulus in peri-screw bone. A quadratic surface regression design was adopted with minimum Akaike information criterion as the stopping rule. All statistical analyses were conducted in JMP Pro 13 (SAS Institute Inc, Cary, NC).

RESULTS

Stepwise multiple regression modelling yielded a model that explained 83.47% of the variation in compressive strain in the PDL. Terms that entered the model are listed in Table 1. Both proximity and force had a linear relation to CS, while the bone elastic modulus had a quadratic relation to CS. Only the proximity covariate had an inverse relation to CS, as indicated by the negative coefficient estimate, while other covariates had direct relationships with CS.

The one interaction term that entered the model was the one between F and E_b. The positive interaction term implied that quality of bone Eb affected the relationship between stress in the PDL and loading magnitude on the miniscrew. Cases with high elastic modulus may have steeper force-stress relationship compared with low-elastic modulus cases, as the interaction plot shows in Figure 4. In other words,

Table 1. Terms of the Multiple Regression Model ($R^2 = 0.8347$) That Explains the Absolute Compressive Stress (g/cm^2) in Premolar Periodontal Ligament[a]

Term	Estimate	Standard Error	$P>\|t\|$
Intercept	–2.334	0.221	$<.0001$
D (mm)	–0.083	0.022	.0004
F (N)	0.125	0.011	$<.0001$
E_b (GPa)	0.140	0.013	$<.0001$
$(E_b$-15.9$)\times(E_b$-15.9)	0.072	0.008	$<.0001$
(F-2.5)$\times(E_b$-15.9)	0.022	0.007	.0022

[a] D indicates proximity of miniscrew implant to periodontal ligament; F, magnitude of loading on miniscrew implant; E_b, peak elastic modulus in the peri-screw bone.

subjects with strong bone properties had more dramatic increases in stresses when the force increases.

The contours of CS in relation to force and bone properties at four different distances between the MSI and PDL implied that high stresses (over 0.5 g/cm^2) were limited to the risk zone, where both bone elastic properties and force magnitude were high enough (Figure 5). The zone became smaller every time the screw was placed farther from the PDL. A loading of 2 N on an MSI generated over 0.5 g/cm^2 stresses in the PDL when two conditions were met: the MSI was less than 0.5 mm off the PDL and the patient had a strong elastic modulus of bone. If the MSI was more than 0.5 mm off the PDL, the CS was expected to always be less than 0.5 g/mm^2 when the loading is 2 N and the bone elastic properties were in the range of the current study values (13.3–17.4 GPa).

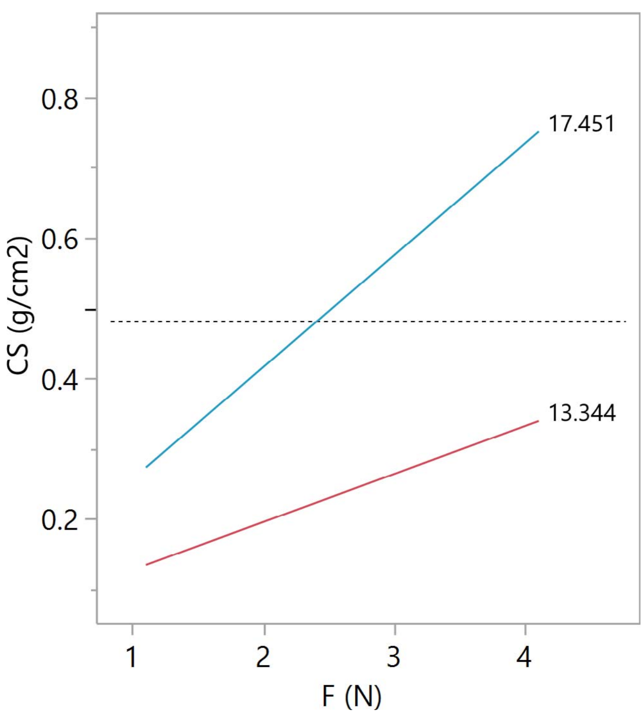

Figure 4. Interaction plot for the stress-force relationship at the extremes of elastic modulus: minimum E_b = 13.344 GPa and maximum E_b = 17.451 GPa.

DISCUSSION

Over the past two decades, a number of studies have investigated the interactions between MSIs and the surrounding anatomical structures.[17–21] The focus was primarily on the interaction between an MSI and bone tissue and on how this particular interaction contributed to the loosening and failure of some MSIs.[17] It was found that factors like overloading of the screw, tooth root proximity, and weak alveolar bone properties may encourage the propagation of excessive strains in the surrounding bone and thereby impair peri-screw bone healing and lead to failure of the screw.[18–21] In contrast, the effects of such factors such as overloading, root approximation, and alveolar bone properties on the PDL and roots were rarely the focus of previous studies. There is a need to understand how MSIs may affect the adjacent PDL and tooth roots. Such understanding would provide insight regarding the necessary measures to protect anatomical structures around MSIs from any potential damage. The current study sheds some light on how the MSI may affect the PDL under various conditions related to three factors: loading, proximity, and bone properties.

Commonly, a 2 N force is used in orthodontic treatment for retracting a canine. At this level of force, the statistical model predicts low stresses in the PDL if the MSI is more than 0.5 mm from the PDL. Based on this estimate, a minimum distance of 0.5 mm between the MSI and the PDL is proposed as a requirement to avoid possible root resorption in adjacent teeth. This proposal is in agreement with the recommendations of Lee et al.[6] who noticed an increased incidence of root resorption when the MSI-root distance was less than 0.6 mm. Several studies have recommended a minimum distance of 1 mm between the MSI and adjacent roots.[21] In the current study, the distance between the MSI and PDL was measured, in other words, the distance to the inner surface of the tooth socket. If the thickness of the PDL (0.1–0.4 mm) is added to 0.5 mm (the minimum distance between the PDL and MSI), a 1-mm distance between the MSI and root surface would be recommended from the results of the current study as well. Some studies recommended even greater distances to account for possible displacement of the MSI.[22]

Recent literature suggests that external root resorption induced by tooth movement depends on multiple cellular and molecular pathways.[12] Likewise, root resorption occurring near an MSI could be a multifactorial problem that may involve all of these cellular and

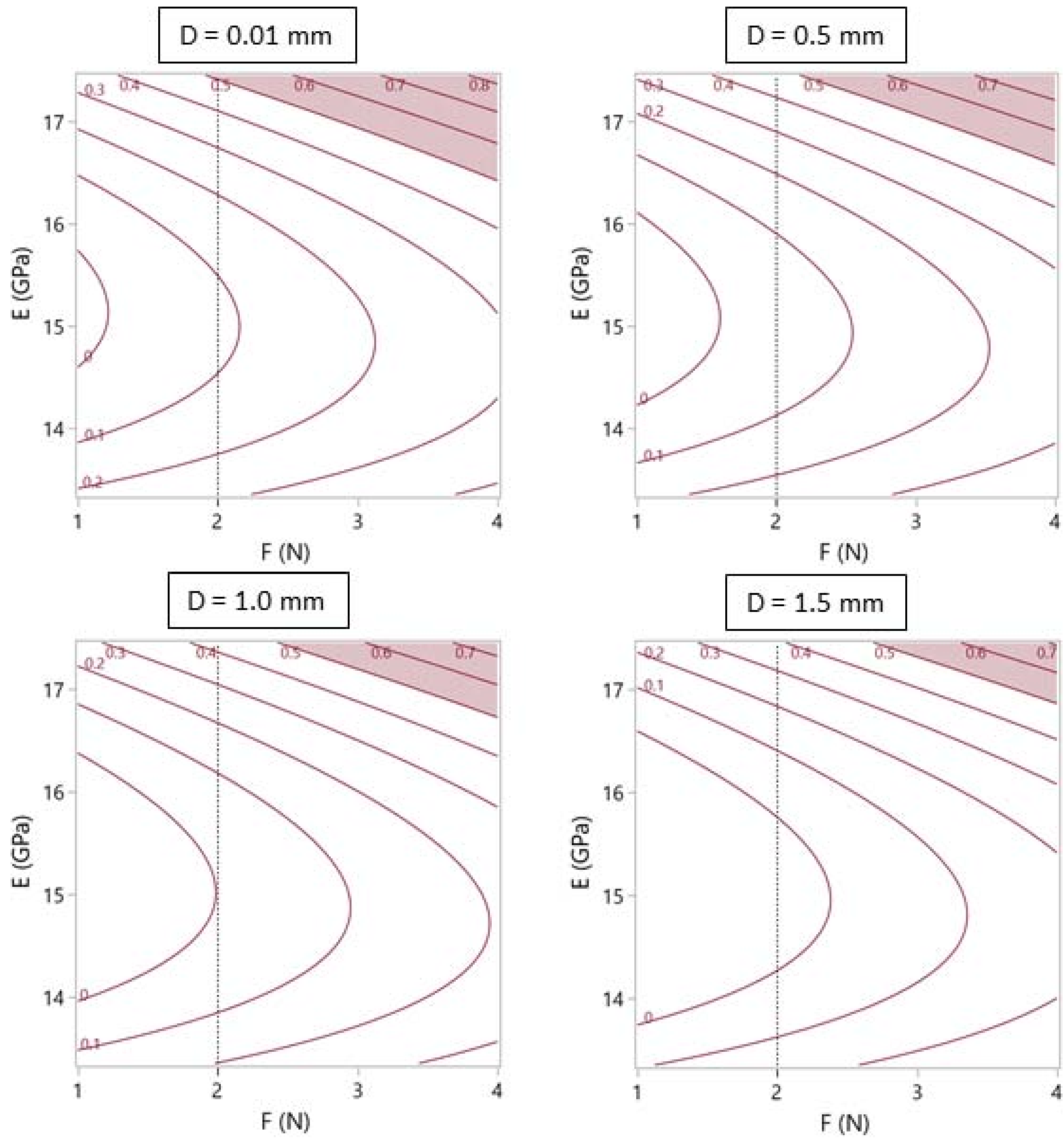

Figure 5. The contours of compression stress show a risk zone (CS > 0.5 g/cm2) where the bone elastic properties and force magnitude are high enough. The zone is smaller every time the miniscrew implant is displaced further from the periodontal ligament.

molecular pathways. MSI-induced root resorption could be merely a consequence of the osteoclastic activity in the thin bone between the miniscrew and PDL.[4] Studies[23,24] have shown that microdamage that develops around MSIs during insertion can extend to a distance of as much as 3 mm, and it is evident that bone microdamage triggers remodeling in bone. The current study, however, may suggest that, under specific conditions, loaded miniscrews may result in compressive stresses in PDL high enough to trigger osteoclastogenesis within the PDL.

It has been shown previously that compressive stress with values as low as 0.5 g/cm^2 may upregulate osteoclastogenesis.[10] The mechanism is mediated by PDL cells, which produce the receptor activator of nuclear factor kappa B ligand, a protein well known for its role in osteoclastogensis.[11] In the current study, compressive stresses on the order of 0.5 g/cm^2 were predicted when the MSI is overloaded (more than 2 N) and placed within a distance of 0.5 mm from the PDL in subjects characterized with strong bone properties. This finding may explain why some MSIs may not cause root resorption while others do, even though both are placed very close to PDL as Lee et al.[6] reported in their study. Some subjects in their study exhibited extensive root resorption, although relatively thick bone was available between the miniscrew and the PDL. The key factor that seems to play a role here, and was not assessed in the study by Lee et al., was the alveolar bone properties. Strong alveolar bone seems to transfer more stresses to the PDL than weak bone, placing the roots at a higher risk of resorption. This was inferred from the direct relationship between CS and E_b in the statistical model. Furthermore, the interaction term in the model implied that subjects with strong bone properties are very sensitive to changes in the force. Slight increases in force may produce significantly higher increases in CS compared with subjects with weak bone properties. This interactive relationship has not been previously reported.

It was advantageous in the current study that bone properties were calculated using CT images rather than considering it as a homogeneous material. Heterogeneous bone properties produced more accurate simulations and predicted stresses.[25] However, a limitation of the current study is that it was not possible to assign nonlinear properties to the PDL due to the limited functions of the software that was used. To overcome this limitation, a low elastic modulus was used for the PDL, as it was compression stresses that were of interest.[26] Confirmation of these findings is needed through a study that combines animal models with subject-specific finite element models. Such a study would confirm root resorption craters in proximity to overloaded miniscrews or miniscrews very close to the PDL.

CONCLUSIONS

- Three factors were found to determine the stress levels in the PDL close to loaded MSIs: the alveolar bone properties, force magnitude, and distance of the MSI to the PDL.
- A minimum distance of 1 mm between the MSI and adjacent roots is required to avoid root resorption in most patients.
- Special attention should be paid in patients with strong alveolar bone elastic properties, as these patients show more susceptibility to the propagation of excessive stresses in the PDL. In such patients, controlling the force and the proximity of the MSI to the PDL are required.

ACKNOWLEDGMENT

This manuscript is based on work presented at the 9th World Implant Orthodontic Conference, Kobe, Japan, in July 2017.

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