TITLE: Inclusion of the PDL in studies on the biomechanical behavior of fiber post-retained restorations – An in vitro study and 3D finite element analysis

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Abstract

Endodontically treated teeth are known to have reduced structural strength. Periodontal ligament (PDL) may influence fracture resistance.

The purpose of this study was to assess the influence of including the PDL in biomechanical studies about endodontically treated and restored teeth.

Forty human maxillary central incisors were treated endodontically and randomly divided into four groups: non-crowned (with and without an artificial ligament) and crowned (with and without an artificial ligament) with glass-ceramic crowns. All groups received prefabricated glass fiber posts and a composite resin core. Specimens were tested, under a flexural-compressive load, until failure occurred. The failure mode was registered for all specimens. The failure loads were recorded and analyzed using an ANOVA test ($P<0.05$). These results were compared with those predicted by a finite element model. The ANOVA did not show significant differences between the use of crown on the failure load ($P=0.331$) and the use of PDL ($P=0.185$). A cohesive mode in crown appeared in crowned teeth and in core in non-crowned group. For non-crowned teeth, and adhesive failure occurred along the cement-enamel junction with a slight tendency in specimens without PDL. Furthermore, an unfavorable failure mode affecting partially the root with no differences regarding to non-crown specimens. In crowned teeth, the tendency was an adhesive failure along the cement-enamel junction. The model predicted a distribution of the safety factor consistent with these results.

The present study showed that inclusion of PDL is not particularly important on biomechanical behaviour of post-retained restorations. However, we recommend its inclusion in fatigue studies.

Keywords

Biomechanics, fiber posts, finite element model, oral rehabilitation, periodontal ligament, restorative dentistry.

Introduction

The use of intraradicular posts is a common retentive technique to restore teeth that have lost a considerable amount of coronal tooth structure. Posts are prefabricated in a range of different materials and designs. Fiber posts can be bonded to the root canal dentin and distribute stresses evenly, so that this type of posts causes fewer fractures.[1–8] For restorations made with fiber posts, more favorable failure modes are reported than in those made with metal posts.[9,10]

To complete the endodontic restoration, an artificial crown could be added, so that an external appearance and functionality, similar to those of the original tooth, are achieved. However, in some cases, the crown is temporarily, or permanently, missing due to economic reasons or other kind.[11] There is a lack of information, in the literature, from studies that analyze the differences, in terms of strength, between teeth restored with a crown and those restored only until the core.

The periodontal ligament (PDL) is a component that surrounds the root of the tooth and connects it to the bone. It is known that the main role of the PDL is load distribution and damping from the tooth to the bone, thus reducing the stress upon the tooth. However, for simplicity or for avoiding dislodgment, a material simulating the PDL is missing[2,12–15] though in other studies, materials based on rubber,[16] a layer of silicone,[6,7,17] along with other materials are used.[18–20] Yoshida et al.[21] showed that the PDL has a modulus of elasticity between 0.11-0.96 MPa, depending on the applied load.

In recent years, finite element analysis (FEA) has been widely used to study the internal stresses in the restored tooth.[22–31] This method has proved to have a number of advantages.

On the one hand, FEA allows complete and complex biomechanical behavior simulations on an anatomical complete model, including cortical and trabecular bones, PDL and all the components of a post-core endodontic restoration or a sound tooth. On the other hand, FEA allows a highly controlled analysis of one or several specific parameters on a single tooth model. This results in a better comprehension of the effect, either individually or combined with different parameters. Moreover, numerical analysis with biomechanical models is faster and cheaper than tooth specimens for *in vitro* experiments or invasive *in vivo* measurements. The validity of the conclusions reached from biomechanical models of the endodontic restoration will depend on the accuracy with which these models can represent the real system. A number of different factors related to the definition of the model conditions, such as the components included in the model, are related to the quality of the results obtained from FEA. Although an increasing number of studies consider all the components of the restored tooth in the models,[32] other studies still simplify the model and not always the PDL is included,[16,33] despite it has been reported that stress distribution is affected to an important degree by this omission.[34] However, performing a bio-mechanical study on a tooth, including its surrounding tissues (cortical bone, trabecular bone and PDL) in the model will increase the accuracy of the results. Over more than a quarter century, erroneous values for the modulus of elasticity of the human PDL have been used.[35] Therefore, the actual influence of including the PDL is still an unsolved matter.

The aim of this study was to assess the influence of the PDL on the strength of maxillary incisors restored with fiber post (with and without crown) and the importance of inclusion of the PDL in biomechanical studies about endodontically treated and restored teeth. To achieve this objective, on the one hand, an experimental fracture strength test was performed on four groups, restored with and without periodontal ligament. All the failure mode were analyzed. ANOVA test analyzed the significance influence on the failure load distribution between teeth with and without PDL. On the other hand, four previously validated 3D finite element models (FEM) which simulated the groups tested on the *in vitro* study were generated in order to analyze the factor of safety (FOS) in the different groups. The results from *in vitro* and finite element model study were compared and analyzed in order to validate the objective.

Methods

Endodontic restoration

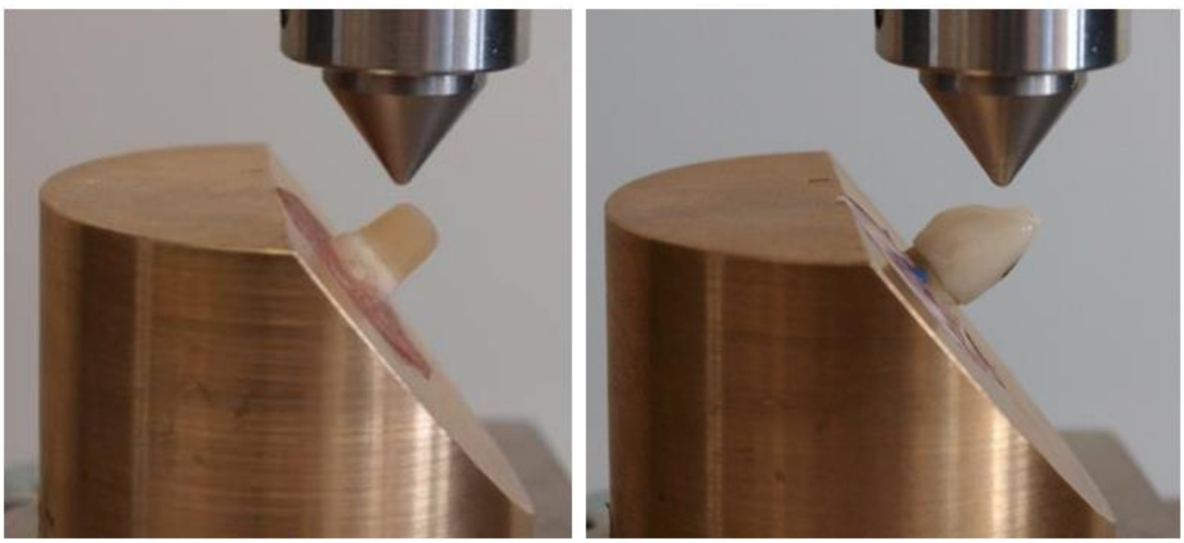
Forty sound human maxillary central incisors, with straight roots, extracted for periodontal reasons, were selected for the study after the corresponding informed consents. Specimens were endodontically treated, and later restored in the same way. The specimens were randomly distributed into two groups, corresponding to two different ways of performing an endodontic restoration: post and core (non-crowned), and post, core and crown (crowned). All specimens were prepared by the same operator following the endodontic treatment described in a previous work.[36] The procedure was as follows: root canals were shaped with the Mtwo system files (VDW, Munich, Germany) in a simultaneous technique and filled with the correspondent gutta-percha points from the same manufacturer, using a continuous wave technique of condensation; we used the Rebilda Post System (VOCO GmbH, Cuxhaven, Germany), a fiber-glass post, and dentinal adhesive, Futura Bond DC, and a flowable material -Rebilda Dual Cure- used for post cementation and for the core (Voco, Cuxhaven, Germany). The crown material was IPS Empress (Vivadent, Schaan, Liechtenstein), a leucite-reinforced glassceramic. After restoration, the teeth were inserted in acrylic resin blocks (Vertex Self-Curing Liquid, Zeist, The Netherlands), which performed the function of the supporting bone. For half of the specimens in each group, a simulated ligament was used, between the root and the resin block, while the other half was inserted directly into the resin. This yielded four different experimental groups of ten specimens each: non-crowned and with ligament (NC-L), non-crowned and without ligament (NC-NL), crowned and with ligament (C-L) and crowned and without ligament (C-NL).

In specimens with a simulated ligament (groups NC-L, C-L), the root was painted using a brush with a layer of Visco-gel (DENTSPLY De Trey GmbH, Konstanz, Germany), prior to being embedded in the block of resin. Visco-gel is a tissue conditioner and temporary soft denture liner based on polyethyl methacrylate. Its modulus of elasticity is close to that of the real PDL, as proven experimentally in a previous study.[36] An average of 0.2 mm thick layer was used, a thickness that is within the range of that of the PDL.[37]

Testing procedure

Specimens were tested under a flexural-compressive load, using a universal testing machine (ELIB-30/W, Ibertest, Madrid, Spain). Specimens were mounted on a bronze mold that was inclined so that the tooth is loaded, on the palatal side, at 50° to the radicular axis, in the vestibular direction, thus simulating the real direction of loads during type I occlusion.[12,38,39]

The load was applied on the core or on the crown (Figure 1), depending on the restoration group, at a controlled speed of 5 mm/min, until fracture of the specimen. The distance from the resin surface till the loading point, along the direction of the root axis, was maintained for all the specimens in the same group. It was greater for crowned specimens (9 mm) than for non-crowned specimens (7.5 mm). Failure was detected by a sharp drop in the force being registered. Both the load applied and the displacement of the loading point were recorded for all the tests. The highest force registered was considered the fracture load. The failure mode and its frequency were registered in all the specimens.



Statistical analysis

Different analyses were performed using the SPSS statistical software version 22 (SPSS Inc., Chicago, Ill., USA).

In order to analyze the influence of the different teeth dimensions on the results, a Multiple Linear Regression was performed, using the failure load as the dependent variable and the root length and mean cervical dimension (average of mesiodistal and buccolingual dimensions) as factors. A significance level of 5% was used in the tests ($\alpha=0.05$).

Results of the previous Multiple Linear Regression did not reveal any significant effect of the dimensions of the restored teeth on the failure load. Thus, an ANOVA was carried out using failure load as the dependent variable, in order to analyze the influence of the following factors: crowned, non-crowned, with ligament and without ligament.

In order to check the assumption of normality, a Kolmogorov-Smirnov test was applied to the standardized residuals and the normality hypothesis was not rejected ($P > 0.05$). The assumption of homogeneity of variances was also accepted.

Finite element model

A 3D FEM of a maxillary central incisor restored tooth was used for the study. This model had been properly validated in previous works.[24,27,29,30] In order to validate the model, a combined theoretical and experimental method was used. In the process, through a static testing, failure loads as well as failure modes were recorded. These results were compared with the stressed area in the finite element model. Model predictions were consistent with the experimental results obtained from the fracture strength test, so the model can be used for studying the biomechanical performance of restored teeth. The model was based on the geometry of a real maxillary central incisor obtained by means of a 3D scanner. The endodontic treatment of the tooth, its later restoration with a prefabricated post, and its insertion in a block of resin were simulated by using the 3D modeling software SolidWorks®. (Dassault Systèmes SolidWorks Corporation, Waltham, MA, USA). This software was used to generate and later assemble the geometries for all the components.

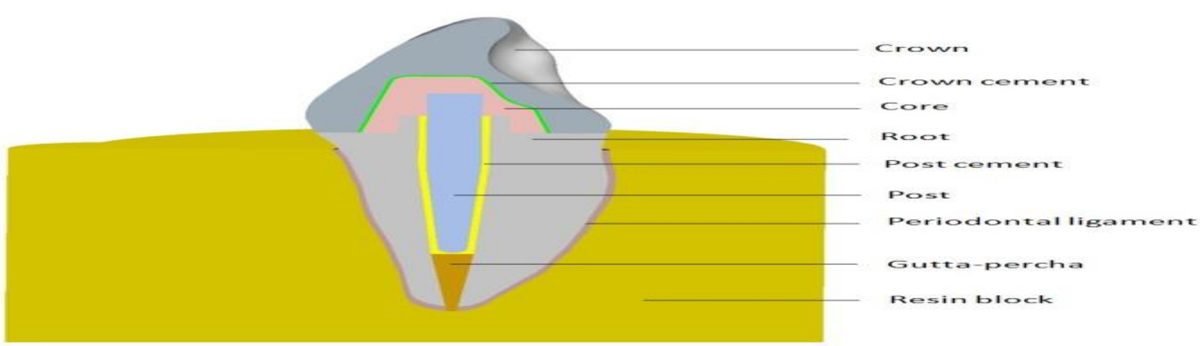
In order to study the effect of the PDL, four models were considered which simulated a real restoration with a cylindrical-conical post, with a diameter of 1.5 mm, as in the testing procedure. Figure 2 shows a sagittal section of the geometrical model for the crowned and with ligament (C-L) group, including all the components that were modeled: resin block, periodontal ligament, root, gutta-percha, post, post-cement, core, crown-cement, and crown. The mechanical properties, for all the component materials of this reference model, were obtained from the literature and from the manufacturers (Table 1). For the sake of simplicity, all materials were considered to be linear and isotropic.

The SolidWorks® Simulation module, available within SolidWorks®, was used to generate a finite element mesh, from the CAD geometry, for each of the models. Solid tetrahedral elements were used, with a mesh control for the maximal size of the elements of 0.3 mm on all the components, except on the block of resin, where a maximal size of 1 mm was considered. The FEA mesher included smaller elements in thin components such as the cement in order to maintain a reasonable value for the aspect ratio. The final models for non-crowned teeth had 225,305 elements defined by 343,434 nodes. Conversely, the final models for crowned teeth had 233,645 elements defined by 348,418 nodes. The validity of the mesh was demonstrated by convergence tests.

A load of 300 N was applied to the palatal side of the tooth, at an angle of 50° to the radicular axis, in the vestibular direction to simulate real biting force (as in the fracture strength test). As boundary conditions, the displacements of all nodes on the lateral surface and base of the block of resin were constrained. The four models were analyzed using the SolidWorks® Simulation module to obtain the stresses at each finite element.

Table 1. Mechanical properties of the materials used in the finite element model.

Component/ material	Elastic modulus (GPa)	Poisson's coefficient	Tensile strength (MPa)	Compressive strength (MPa)	References
Root	18.6	0.31	106	297	[22,25,40–45]
Gutta-percha	0.00069	0.45	15	15	[22,40,41,46]
Periodontal ligament	0.00125	0.45	2	2	[22,47]
Resin block	2.028	0.30	120	180	Manufacturer
Futurabond DC adhesive	10	0.30	106	242	Manufacturer
Rebilda DC (core)	10	0.30	125	285	Manufacturer
IPS Empress®	62	0.30	160	162.9	Manufacturer and [48]
Dual cement	10	0.30	106	242	Manufacturer and [49]
Glass Fiber post	20	0.30	1200	340	Manufacturer



Results

Results from the Experiment

Figure 3 shows the failure modes observed for all the groups. Furthermore, the failure frequency (%) in each of the cases was reported (Table 2). The failure mode type B was considered as unfavorable failure mode, affecting partially the root below the resin level. This type of failure appeared in 30% of cases in each non-crowned group (with ligament and without ligament) and in 40% of cases in each crowned group (with ligament and without ligament), thus no significant effect appeared between groups and between with and without ligament within each group.

The rest of the failure modes were considered favorable. Other no significant effect, in crowned group, was the cohesive failure mode in crown type E and F. Both failures appeared in the same proportion (20%) in specimens with PDL and without PDL.

According to the cohesive failure mode in core (A) in non-crowned specimens, a 30% more failures of this type of failure mode appeared in specimens with ligament than without ligament, meaning a slight significant effect.

Studying the adhesive failure in the crown-dentin interfaces (type C), an effect appeared when comparing the two groups, as more cases appeared in crowned specimens. In addition, the percentage was higher in specimens without PDL (40%) than in those with PDL (20%). On the contrary, in crowned group, the effect was different (70% appeared in specimens with PDL and 40% in specimens without PDL). Finally, only a 10% of a vestibular failure in core (D) was detected only in specimens without PDL. Some specimens tested till failure are shown in Figure 4.

Results from the statistical analysis

Results of the Multiple Linear Regression did not reveal any significant effect of the dimensions of the restored teeth on the failure load (P=0.397 for mean cervical dimension, and P=0.239 for root length).

From the ANOVA test, no significance influence on the failure load distribution was found between teeth with and without PDL (P=0.185). Likewise, the same result was found between groups crowned and non-crowned teeth (P=0.331).

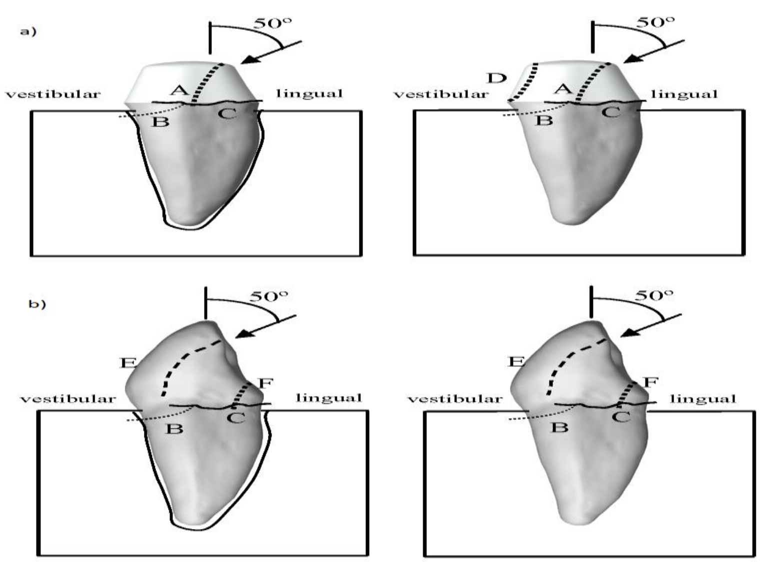


Table 2. Percentage of failure mode in each group.

Failure mode	non-crowned		crowned	
	with PDL	without PDL	with PDL	without PDL
A	70%	40%	-	-
B	30%	30%	40%	40%
C	20%	40%	70%	40%
D	-	10%	-	-
E	-	-	20%	20%
F	-	-	20%	20%

Results from the Finite Element Analysis

In this section, the results of the study of the inclusion of the PDL are presented. Instead of showing the stress distribution achieved, the more visual option of presenting the Factor of Safety (FOS) distribution is shown. The FOS has been calculated, for each component, as the ratio between the strength of the component material and the maximal von Mises stress (predicted by the finite element model) in that component. Tensile and compressive strengths (MPa) of each component material, obtained from literature, are presented in Table 1. A smaller factor of safety means that the component is more prone to failure. The smallest FOS of the components can be considered as the FOS of the overall system. As the saying goes, “A chain is only as strong as its weakest link”.

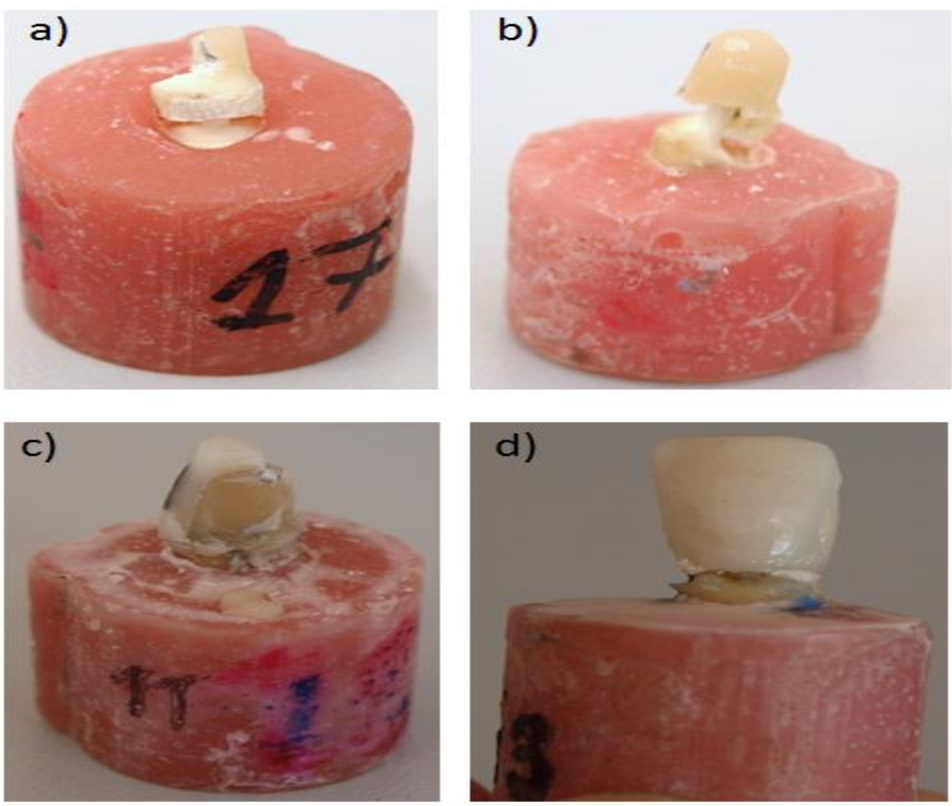
Figure 5 shows the FOS predicted by the model: for the non-crowned teeth (upper side) and for the crowned teeth (bottom side). Warmer colors represent lower FOS. When considering the non-crowned teeth (upper side), the smallest FOS, with and without PDL, are in the interface between post and core. Bending moment, due to inclusion of the PDL, causes a bigger area with lower FOS in the system. In the crowned teeth, the smallest FOS, with and without PDL, are in the crown. Likewise, bending moment, due to inclusion of the PDL, causes a bigger area with lower FOS in the system.

Discussion

The influence on the strength of forty maxillary incisors restored with fiber post (with and without crown) subjected to a flexural compressive load was analyzed through an *in vitro* study. In a previous work,[36] twenty specimens half of the specimens with simulated ligament were studied. However, the value of variance associated to fracture load close to significance (0.09) obtained from the statistical analysis, showed that a greater number of specimens were needed. Furthermore, no finite element study was realized in order to clarify the results and support the results.

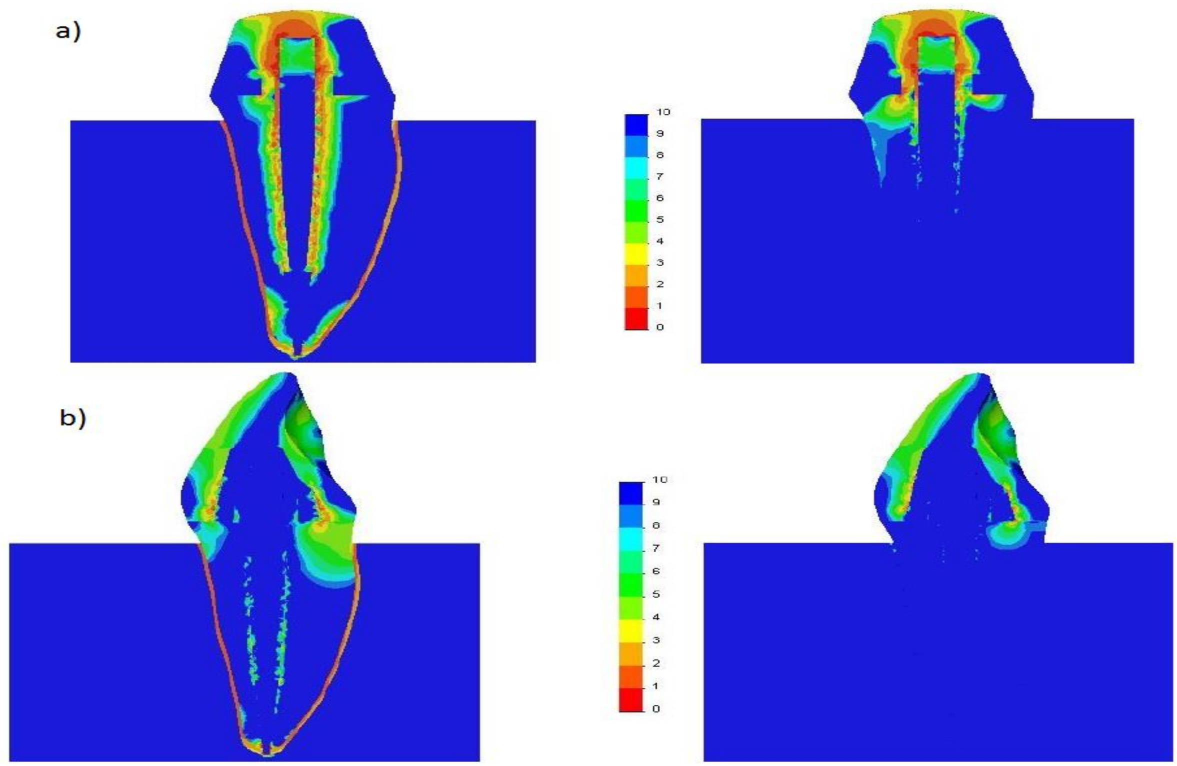
As it is known, *in vitro* studies which involve endodontic restorations have high costs, and collect teeth in optimal conditions imply a high difficulty. In the present study, twice of specimens relative to the previous study, were analyzed. The results from the ANOVA test, with a significance level of 5% used in the tests (α=0.05), showed that no statistically significant differences were found between specimens with and without PDL (P=0.185), with regard to the failure load. A similar conclusion was reached when comparing the two groups of crowned teeth (crowned and non-crowned) (P=0.331). The results from Kolmogorov-Smirnov test showed that the assumption of homogeneity of variances could be accepted.

Failure under flexural loads, in crowned and non-crowned teeth, can be compared to previous experiments performed with the same load orientation. Al-Omiri & Al-Wahadni[12] found similar strength values to those obtained in the present study for teeth restored with glass-fiber posts and core, without a crown. Akkayan & Gulmez[50] tested the fracture load of teeth restored using glass-fiber posts with core and metal crowns, with the incorporation of a simulated ligament. Fracture loads reported in that work were in the range of 75–99 kg. These loads are higher than the results obtained in the present work for crowned teeth. This may be because that study was performed using maxillary canines instead of incisors and teeth were restored with a metallic crown, whereas the crowns in our work are made of a glass-reinforced ceramic.



The experimental findings were corroborated with the results from the model. The failure modes associated with each of the groups, can be estimated from the safety factor obtained from the models. As it is shown in Figure 5, the FOS distribution yielded was quite similar between teeth with (left) and without PDL (right) for both groups: crowned (upper side) and non-crowned (bottom side). The failure A, E and F, were predicted by the model from the concentration of small FOS in the interface between post and core (A), in the crown (F), and in the interface between core and crown at the vestibular aspect (E). In all cases, a concentration of small FOS appeared in the CEJ, although smaller FOS appeared at the vestibular aspect than at lingual aspect, which may explain the appearance of the adhesive failure (C). Furthermore, low safety factors appeared concentrated along the post cement and upper zone of the root. This fact, can explain the appearance of the failure mode type B considered as unfavorable failure mode affecting partially the root below the resin level at vestibular aspect.

However, the model estimated a bigger area with lower FOS in the case of teeth with PDL (for both crowned and non-crowned groups), due to the increased bending moment. This fact can be related with the results of a work [51] based only in a finite element study. In this study when the periodontal ligament or the root dentine was removed, the variation in nodal stresses increased dramatically. But as it is mentioned by the author, two limitations should be considered. First, the results of this study must be interpreted with a certain amount of caution as that analysis was a two-dimensional plane strain analysis so it was not possible to model any twisting movements of the tooth in the z direction. And secondly, a more mesially or distally placed slice would give less tooth movement and presumably lower stresses.



We think that the bigger area obtained with lower FOS in the case of teeth with PDL, obtained with our finite element model, it would be more apparent in a study dealing with dynamic loads, due to micro-crack propagation. Thus, inclusion of the periodontal ligament in fatigue studies is mandatory. Nonetheless, theoretical fatigue studies have the disadvantage that S-N curves, for most of the restorative materials, are still unknown and must be estimated [52]. The median for failure loads for crowned teeth was 292 N (with PDL) and 280 N (without PDL), whereas for non-crowned teeth it was 538 N (with PDL) and 395 N (without PDL). Biting loads on incisors have been reported to be close to 140–200 N.[53]

Conclusion

Including the PDL in a FEA model will only increase the accuracy of the results. Therefore, periodontal ligament should be included when an in vitro or a finite element study is realized. Thus, we recommend including the periodontal ligament in fatigue studies too.

However, in the presented *in vitro* study the inclusion of the artificial periodontal ligament did not have any significant influence upon the strength of the endodontically treated teeth. The proposed finite element models, predicted a distribution of the safety factor (FOS) consistent with the results obtained from the *in vitro* study, explaining and corroborating the failure mode observed in the specimens and the lower FOS obtained through the model.

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Conflict of interest

The authors declare that there are no conflicts of interests in writing this article.

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