Analysis of the effect of design parameters and their interactions on the strength of dental restorations with endodontic posts, using finite element models and statistical analysis.

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Many previous studies, both *in vitro* and with model simulations, have been conducted in an attempt to reach a full understanding of how the different design parameters of an endodontically-restored tooth affect its mechanical strength. However, differences in the experimental set-up or modelling conditions and the limited number of parameters studied in each case prevent us from obtaining clear conclusions about the real significance of each parameter. In this work, a new approach is proposed for this purpose based on the combination of a validated 3D parametric biomechanical model of the restored tooth and statistical analysis using full factorial analysis of variance. A two-step approach with two virtual tests (with, respectively, 128 and 81 finite element models) was used in the present work to study the effect of several design parameters on the strength of a restored incisor, using full factorial designs. Within the limitations of this study, and for cases where the parameters are within the ranges that were tested, the conclusions indicate that the material of the post is the most significant factor as far as its strength is concerned, the use of a low Young's modulus being preferable for this component. Once the post material has been chosen, the geometry of the post is of less importance than the Young's modulus selected for the core or, especially, for the crown.

Keywords: prefabricated posts; finite element analysis; factorial design.

1. Introduction

Advances in endodontic restoration in dentistry have generalized the use of prefabricated posts for restoring devitalized teeth. The choice of the appropriate post, core and cement is crucial for the successful outcome of the restoration procedure

(Stockton 1999; Monticelli et al. 2008). However, the large variety of these restoration components that are available commercially, together with the lack of conclusive results from previous studies, makes it extremely difficult to choose one or another. Therefore it would be very useful to know the effect that the different parameters in a tooth restoration with a prefabricated post have on the subsequent mechanical performance of the restoration, but the interaction among these parameters also needs to be established.

Previous studies (González-Lluch et al. 2014) highlighted that, although a large number of *in vitro* studies in the literature have investigated the effect of different restoration parameters, such as the post material, length, diameter or longitudinal shape, contradictory results have been obtained in some cases (Standlee et al. 1972; Kurer et al. 1977; Ruemping et al. 1979; Miller 1982; Cooney et al. 1986; Felton et al. 1991; Standlee & Caputo 1992; Chang & Millstein 1993; Zalkind et al. 2000; Balbosh & Kern 2006). For example, some studies found that the restoration was stronger with the use of fibre posts than when metallic posts were employed (Isidor et al. 1996; Akkayan & Gülmez 2002; Barjau-Escribano et al. 2006; González-Lluch et al. 2009), others (Raygot et al. 2001; Hu et al. 2003) did not observe any significant differences and still others (Sidoli et al. 1997; Martinez-Insua et al. 1998) concluded that restorations with metallic posts are stronger than those with composite fibre posts. Moreover, different conclusions about the influence of the post length on stress distribution were obtained in different studies (Davy et al. 1981; Holmes et al. 1996; Rodríguez-Cervantes et al. 2007). While some showed a slight change in stress distribution for different post lengths (Davy et al. 1981), others obtained an increase in stress with short posts (Holmes et al. 1996) and several others reported no influence of the post length regardless of the post material used in the restoration (Rodríguez-Cervantes et al.

2007). Finally, some studies (Pilo & Tamse 2000) recommend 1 mm of dentine around the post, so a tapered post could be a good alternative. However, other studies showed poorer resistance and more irreparable failures in restorations with tapered posts than with parallel-sided posts (Sorensen et al. 1990).

Most of the works mentioned above are *in vitro* studies. As is well known, random variability is an important drawback in an *in vitro* study. Alternatively, finite element analysis (FEA) can be used to avoid this problem, thereby making it a useful tool to estimate the performance of endodontic restorations and to compare this performance with different configurations unlike experimental *in vitro* tests. FEA makes it possible to perform a highly controlled analysis of one or several specific parameters of a single tooth model, resulting in a better understanding of the effects of multiple parameters. However, many FEA studies from the literature usually analyse the effect of just one (Toparli 2003; Okamoto et al. 2008; Soares et al. 2010) or two design parameters (González-Lluch et al. 2009; Hsu et al. 2009; Chuang et al. 2010). Furthermore, in most FEA models the effect of each endodontic parameter is analysed through the stress distribution, instead of using the failure load, which is commonly used for comparison in *in vitro* studies. The failure load can be obtained by comparing the maximal stress in the model with the material strength.

In the previous work by the authors cited above (González-Lluch et al. 2014), FEA was used to study the effect of varying several specific parameters of a single tooth restoration on its mechanical performance, using a sensitivity analysis approach. Twenty different characteristic parameters of the restoration (geometrical and restorative material properties) were selected and they were modified in twenty different sensitivity analyses, only one parameter being modified each time. This approach allowed drawing conclusions about the parameters with the greatest influence on the mechanical strength (defined as safety factor to failure) starting from a reference model of a restored incisive. The loading angle was shown to be the most influential parameter, followed by the Young's modulus of the post, the diameter of the post at both the radicular and coronal ends, and the length of the post inserted into the root. However, that work did not include a detailed analysis of the cross influence of the parameters, although a preliminary analysis did show that the effect of varying a parameter separately changes when combined with variations in a second parameter.

In order to assess the significance of each design parameter in the final mechanical strength, it would be desirable to have a full factorial design in which all possible parameters’ values or levels are combined across all the other parameters’ values. The statistical method of analysis of variance, ANOVA, would thus make it possible to establish which parameters have a statistically significant effect on the mechanical strength. Taking this into account, in the present work and to our knowledge for the first time, the authors present a new approach that combines FEA with statistical analysis with the aim of understanding how the interaction among design parameters affects the strength of dental restorations performed with endodontic posts in order to obtain clear conclusions that enable us to move towards optimal designs.

2. Material and Methods

A 3D finite element model (FEM) of a maxillary central incisor-restored tooth was defined, based on the geometry of a real tooth. That model had been properly validated and used in previous works (Barjau-Escribano et al. 2006; Rodríguez-Cervantes et al. 2007; González-Lluch et al. 2009; González-Lluch et al. 2014). Figure 1 shows a sagittal section of the geometrical model, including all the components that were modelled, namely bone (cortical and trabecular components), periodontal ligament (PDL), root, gutta-percha, post, post-cement, core, crown and crown-cement. A width of 10 mm in the mesiodistal direction was considered for the bone model.

Several geometrical parameters were considered to define the restoration (Figure 1). Some of these geometrical parameters and some of the material properties of the restorative components were considered as variables to simulate different restoration alternatives. However, based on the results of our previous study (González-Lluch et al. 2014), other parameters were kept constant in the present work, because they were found to be less significant in the final strength. The values of the geometrical parameters that were considered constant in this work are shown in Figure 1, and Table 1 shows the material properties not modified in our analysis. All the materials in the model were considered to be linear and isotropic.

A two-step approach was used, based on two different virtual tests. In the first test, seven parameters were taken as factors, with two different levels for each factor, and a total of 2^7=128 models were defined from the full factorial combination of these seven parameters, each of them representing a different restorative solution. Four of the seven factors were geometrical parameters of the post (D_{p2}, L_{pr}, $r_d=D_{p1}/D_{p2}$, $r_c=L_{prc}/L_{pr}$, see Figure 1) and the other three are the material properties (Young's moduli and strength) of the three main restorative components: post, core and crown (E_{post}, E_{core}, E_{crown}). These seven factors were selected because of their greater influence on the final strength of the restoration, as shown by the results of our previous work, in which the sensitivity of twenty different parameters was analysed (González-Lluch et al. 2014). The parameters r_d and r_c are relative parameters, indicating the relationship between the radicular and coronal diameters of the post and the ratio of the length of the cylindrical portion to the total radicular length of the post, respectively. An ANOVA test was used to investigate the significance of these seven factors and their interactions in the final strength of the restoration. As post material revealed as the most important factor, a second ANOVA was conducted including only cases for the best post material. A second virtual test was designed to refine the results of the first test. The selection of the parameters for this second test was based on the results of the first test, including the significant factors in the second ANOVA above cited, restricted to the best post material, as will be explained in the results section. Four parameters at three levels were selected for this second test (D_{p2}, E_{post}, E_{core}, E_{crown}). A full factorial design of 3^4=81 models was obtained with all the combinations of these parameters, representing 81 different restorative solutions. A new ANOVA test was conducted to test the significance of these factors and levels in the mechanical strength.

Table 2 presents the parameter values used for the geometrical factors in the first and second full factorial tests. Table 3 shows the values used for the material properties of the main restorative components used in the virtual tests. Young's modulus (E) and the Poisson coefficient (ν) were taken from the reported research or from data provided by the manufacturers of restorative components (citations included in the table). Tensile strength (TS) and compressive strength (CS) were also taken from published data or estimated using published information for the crown and the core, when they do not correspond to actual dental materials. It must be noted that each material in the model is characterized by four parameters, E, ν, TS and CS, although the factor *material* is denoted in short as E in the ANOVA tables.

The Pro/Mechanica module, available within Pro/Engineer, was used to generate the finite element mesh, from the CAD geometry, for each of the 128 models in the first test and 81 models in the second test. Bonded interface was considered in all adjacent components. Solid tetrahedral elements were used, with a mesh control for the maximum size of the elements of 0.3 mm on all the components, except on trabecular and cortical bone, where a maximum size of 1 mm was considered. The 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 had nearly 511,000 elements defined by approximately 88,000 nodes. The validity of the mesh was established by convergence tests in previous works with the same model.

A load of 300 N was applied to the crown at 50 degrees to the radicular axis in the vestibular direction (Figure 1), thereby simulating the real direction of loads in anterior teeth (Al-Omiri & Al-Wahadni 2006) and the magnitude of the fracture load obtained in experimental studies with this load inclination (Sorensen et al. 1990; Heydecke et al. 2002). As boundary conditions, the displacements of all nodes at the base of the cortical and trabecular bones, as well as the mesiodistal displacements of the nodes in the lateral sections of the bones, were constrained.

All the models generated were analysed using MSC-Nastran (MSC Software Corp., Santa Ana, CA, USA) to obtain the stresses at each finite element. For each component, the stresses were compared with the tensile and compressive strengths of its material, using the failure criterion proposed by Christensen (Christensen 2005; Pérez-González et al. 2011) to calculate a ‘cohesive safety factor’ at each finite element (a simple ratio that is intended to be greater than one, so that strength must be greater than stress). This criterion was used instead of von Mises because it is valid for both ductile and brittle materials. The von Mises criterion is appropriate only for ductile materials with equal compressive and tensile strength (De Groot et al. 1987), but it is not appropriate for brittle materials that are frequently present in endodontic restorations (ceramics, cements or resin composites). Using this criterion, the three principal stresses on each element $\sigma_1 \geq \sigma_2 \geq \sigma_3$ are combined with TS and CS to obtain a safety factor through equation 1, where *k* is the ratio of CS to TS (equation 2), I_1 is the first invariant of the stress tensor (equation 3), and J_2 is the second invariant of the deviatoric stress tensor (Pérez-González et al. 2011).

$$SF = \min\left(\frac{CS}{\max(0,-\sigma_3)}, \frac{TS}{\max\left(\max(0,\sigma_1), \frac{(k-1)}{2k} \cdot I_1 - \sqrt{\left(\frac{k-1}{2k}\right)^2 \cdot I_1^2 - \frac{1}{k} \cdot 3 \cdot J_2} \right)} \right) \tag{1}$$

$$k = \frac{CS}{TS} \tag{2}$$

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \tag{3}$$

$$J_2 = -\frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right] \tag{4}$$

However, the Christensen criterion is valid for checking cohesive failure, but does not predict the possible adhesive failure between components bonded by the cement. To predict the possible adhesive failure between components bonded by the cement, the maximum shear stress at each finite element of the cement was compared with the admissible shear stress of the bonding cement (half the tensile strength of the cement) to define an 'adhesive safety factor'. The lowest of the cohesive and adhesive safety factors was considered the safety factor at each finite element of the cements.

To avoid possible errors in estimating exact stress in stress concentration areas, the 'component safety factor' was calculated at each component as the average of the safety factors at the finite elements of the component with safety factors below the 0.5 percentile. The objective of this procedure was to soften the possible effect of very localized stress peaks in the model, due to the discretization error, which could distort the results. The failure of any restorative component requires the existence of a region with a significant volume below a low safety factor for the progression of the failure to take place. Discarding these very localized peaks in the stress distribution is a common engineering practice. The ‘overall safety factor’ of the restored tooth (SF) was calculated as the lowest of the component safety factors. Safety factor values lower than unity indicate that the material is prone to have a mechanical failure at this point, and values greater than unity indicate a safe condition at this point. Post-processing was performed with MSC-Patran (MSC Software Corp., Santa Ana, CA, USA) and the Matlab program (MathWorks, Natick, MA, USA). In order to simulate possible random variations in the material properties, the safety factor was computed three times for each model, one with the reference mechanical properties shown in Table 3 and two others that considered a random variability within the range of ±3% in the tensile and compressive strengths of the restorative materials, close to some variability reported in the properties of dental materials (Chung et al. 2004; Stewardson et al. 2010). That gives us a triplet of safety factors for each model, thus representing slightly different virtual specimens with the same endodontic restoration. Finally, the analysis of the results was performed using the PASW Statistics 22 software (SPSS Inc., Chicago, IL, USA). Different ANOVA on the global safety factor were computed for the first and second test, taking the parameters changed and their interactions as factors. A significance level of 5% was considered in all the tests ($p=0.05$).

3. Results

Figure 2 shows a box plot of the components safety factors for the first virtual test, the lowest values being presented by the root and the cements. The variation in the safety factor across the different restoration models is small in the root and the crown-cement, and higher in the rest of the components. The location of the weakest point was always in the post cement for a high Young's modulus post and in the dentine for a low modulus post.

The results of ANOVA on the overall safety factor (SF, the minimum of the component safety factors in each model) for the first test are shown in Table 4. Four parameters were found to have statistically significant effects on the SF: the Young's modulus of the post (E_{post}), the post diameter (D_{p2}), the post length (L_{pr}) and the ratio between cylindrical and total length of the post (r_c), whereas the other three parameters were not significant. The Young's modulus of the post (E_{post}) is the parameter with the greatest effect ($p<1e-10$). ANOVA was then repeated including two-factor interactions, and a clearly significant effect was also found for the following five interactions ($p<1e-5$): $E_{post}*D_{p2}$, $E_{post}*r_c$, $E_{post}*L_{pr}$, $D_{p2}*r_c$, $D_{p2}*r_d$ and also for two more interactions ($p<1e-2$): $L_{pr}*r_d$ and $L_{pr}*D_{p2}$. The mean overall safety factor at the two different levels of E_p (Table 5) showed that the mean strength with a low Young's modulus of the post, E_{post}=30 GPa (1.18), is 30% greater than that with a higher Young's modulus, E_{post}=207 GPa (0.90). Figure 3 shows a representation of the SF in three sections (frontal, sagittal and transversal) of two models in test 1 with different post material (E_{post}=30 GPa in Figure 3a and E_{post}=207 GPa in Figure 3b), but equal values for the rest of parameters (E_{crown}=62 GPa, E_{core}=15 GPa, L_{pr}=7 mm, D_{p2}=1.2 mm). Warmer colours represent lower SF. The SF in the post is not displayed in this figure to allow a better view of the SF in more critical components such as dentine and post-cement. The results showed a greater variation in the safety factor among cases for the high modulus post (SF between 0.71 and 1.14) than for the low modulus post (SF between 1.12 and 1.25).

Given the significant interaction of the Young's modulus of the post with other parameters, a new ANOVA was computed (Table 6) restricted to the cases with a low Young's modulus of the post. Taking into account the small variation in the SF with a low Young's modulus, the cases with random variation in the material properties were not included in the ANOVA to avoid distortion of the analysis. The results indicated that in those cases E_{core}, E_{crown} and D_{p2} have a significant effect on the strength, whereas L_{pr}, r_c and r_d are not statistically significant. Based on this result, these three significant parameters were selected for the second test, together with the Young's modulus of the post, for which variations near 30 GPa were considered in this second test (see Table 3).

Table 7 shows the results of ANOVA on the SF for the second test, with four factors at three levels and a low Young's modulus for the post. Results reveal a significant effect on the SF of the Young's modulus of the crown and the Young's modulus of the core, this latter being close to the significance limit ($p=0.037$). Figure 4 shows a comparison of the SF for three models with different material for the crown and equal values for the rest of the parameters ($E_{post}=30$ GPa, $E_{core}=15$ GPa, $L_{pr}=7$ mm, $D_{p2}=1.2$ mm). The location of the weakest point is in the dentine for the models with a higher Young's modulus in the crown (62 GPa and 124 GPa) and in the load application area of the crown for the low modulus cases (30 GPa). The greatest mean SF is obtained with $E_{crown}=62$ GPa (1.19) with a similar value for $E_{crown}=124$ GPa (1.17) and a clear drop for $E_{crown}=30$ GPa (0.76).

On restricting the analysis to cases with $E_{crown}=62$ GPa, only the coronal post diameter (D_{p2}) becomes significant on strength, $D_{p2}=1.2$ mm being the best option, with small differences (less than 2%) with respect to $D_{p2}=1.0$ mm or $D_{p2}=1.4$ mm.

4. Discussion and conclusions

A new approach that combines FEA with statistical analysis as a means to analyse dental restorations with endodontic posts is presented in this paper. It is based on the use of a parametric FEM of the restored tooth and establishing full factorial virtual tests including variations of the values for the different parameters considered in the model. ANOVA analysis is used to decide which of these parameters are significant in the strength of the restoration. In the present work, strength is evaluated by means of an overall safety factor among components (SF) obtained using the Christensen criterion for cohesive failure and the maximum shear stress criterion for adhesive failure (Christensen 2005; Pérez-González et al. 2011).

The results of the present work confirm that the material of the post is the most important factor for the biomechanical performance of the restored tooth, and exerts a significant effect on the final strength. The analysis of the critical point of the restoration revealed that the failure tended to start in the dentine, at the lingual cervical area of the root, for the low modulus post (Figure 3a), and in the post-cement for the high modulus post (Figure 3b). These results are consistent with several previous studies using both *in vitro* tests (Isidor et al. 1996; Sidoli et al. 1997; Martinez-Insua et al. 1998; Akkayan & Gülmez 2002; Barjau-Escribano et al. 2006) and based on FEA (Lanza et al. 2005; Barjau-Escribano et al. 2006; Nakamura et al. 2006; Pest et al. 2006; Okada et al. 2008).

The use of post materials with a low Young's modulus (near 30 GPa, such as glass fibre) is preferable to achieve stronger restorations and reduce stress concentration at the post-dentine interface, in contrast to what happens when a high modulus material is used for the post (207 GPa, typical of steel). The improvement in strength is about 30% on average (Table 5).

The results also indicate that the effect of other geometrical design parameters, such as post diameter or post length, is dependent on the post material selected, because a significant interaction between these geometrical parameters and the Young's modulus of the post was obtained. This result has a clear clinical implication: post geometry should be selected depending on the post material. Other previous works have reported that restoration with glass fibre posts is less sensitive to the geometry of the post (Barjau-Escribano et al. 2006; Pest et al. 2006; Rodríguez-Cervantes et al. 2007), that can be explained by the similar elasticity between dentine and post in that particular case. This result is confirmed in the present work. Moreover, our results indicate that if low modulus materials are used for the post, the selection of the Young's modulus for the crown has a greater influence on the strength than the variation of the modulus of the post within the range of 12 to 48 GPa (Table 7). The analysis of the SF in the model when the modulus of the crown is changed (Figure 4) showed that the starting point of the failure is located in the root for high modulus crown material (E_{crown}=124 GPa, E_{crown}=62 GPa) and in the load application area of the crown for low modulus crown material (E_{crown}=30 GPa). The results reveal that once a low Young's modulus has been selected for the post, the effect of the post diameter is no longer significant and it is the selection of the materials for the core or especially for the crown that becomes more important (Table 7).

The validity of the conclusions of the present work may be limited by how correctly the models represent a real endodontic restoration and by the correct estimation of the material properties, i.e. Young's modulus and tensile and compressive strengths. Moreover, the conclusions may not be right for values of the parameters outside of the selected ranges, although these ranges do cover current clinical practice.

The model used in the present work is an evolution of that used by the authors in several previous studies and has been validated from experimental tests on real endodontic restorations (Barjau-Escribano et al. 2006; Rodríguez-Cervantes et al. 2007; González-Lluch et al. 2009; González-Lluch et al. 2014). It is based on the geometry of a real incisor and is three-dimensional. The validity of the mesh has been proved by convergence tests to demonstrate that the size of the finite elements used is suitable to be able to obtain a good representation of the stress distribution. Our model is linear, which is a limitation for the exact representation of some components such as the ligament. However, although the effect of excluding the ligament in the model has been demonstrated to lead to important errors in previous works, the differences in stress distribution between a linear and non-linear model of the PDL are of less significance (Maceri et al. 2010). On the other hand, some materials of the restoration, such as dentine, present an anisotropic behaviour. In this sense, some recent works have used orthotropic models for dentine (Ferrari et al. 2008), but the differences in the elastic modulus for the different directions were small, and consequently this limitation probably does not affect the conclusions of the present work.

The material properties considered for the different models of the restoration (Table 3) are based on data published in the literature and also on information provided by the manufacturers of certain restorative components. In a number of cases the tensile and compressive strengths for some materials used in the model were estimated using ratios between the Young's modulus and the strength obtained from reported research (see Table 3). These estimations could affect some of the conclusions of the present work to a certain extent. However, this limitation has been partially avoided by generating three different virtual specimens for each model, a random variation in the material strength around the reference value being considered for each of them.

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Table 1. Mechanical properties of the materials with constant value in the simulations (E: Young’s modulus, ν: Poisson coefficient, TS: tensile strength, CS: compressive strength)

Material (Component)	E (GPa)	ν	TS (MPa)	CS (MPa)	References
Dentine (Root)	18.6	0.31	06	297	(Asmussen et al. 2005; Powers & Skaguchi 2011)
Gutta-percha	0.00069	0.45	15	15	(Friedman et al. 1975; Genovese et al. 2005; Asmussen et al. 2005)
Ligament (PDL)	0.0689	0.45	2	2	(Asmussen et al. 2005)
Cortical bone	13.7	0.30	120	180	(Burstein et al. 1976; Asmussen et al. 2005)
Trabecular bone	1.37	0.30	9	4	(Asmussen et al. 2005; Henriksen et al. 2011)
Dual cement (Post cement, crown cement)	10	0.30	106	242	IV*, (Saskalauskaite et al. 2008)

* IV: Ivoclar Vivadent, AG, Schaan, Liechtenstein

Table 2. Different levels used for the geometrical parameters in the virtual tests

Parameter	Description	Test 1	Test 2
D_{p2} (mm)	Diameter of the post at the coronal height	1.2, 1.8	1.0,1.2,1.4
L_{pr} (mm)	Length of the post inserted into the root (from the cement-enamel junction)	7.0, 12.0	7.0
r_c	Ratio between cylindrical part length and total length of the post, L_{prc}/L_{pr}	0.3, 0.8	0.3
r_d	Ratio between radicular to coronal diameters of the post, D_{p1}/ D_{p2}	0.3, 0.8	0.8

Table 3. Different levels considered for the mechanical properties of the materials of the three main restorative components in the virtual tests (E: Young's modulus, ν: Poisson coefficient, TS: tensile strength, CS: compressive strength)

Component	E (GPa)	ν	References for E, ν	TS (MPa)	CS (MPa)	References for TS, CS	Test
Crown	124	0.3	IPS Empress 2®	480	488.7	Estimated from (Holand et al. 2000; Albakry et al. 2003) and IV*	1,2
	62	0.3	IPS Empress®, IV*,(Albakry et al. 2003)	160	162.9	IPS Empress®, IV*, (Pröbster et al. 1997)	1,2
	30	0.3	N/A	55.3	54.3	Estimated from (Holand et al. 2000; Albakry et al. 2003) and IV*	2
Core	45	0.24	(Xu et al. 2000; Wang et al. 2007)	250	285	Estimated from (Xu et al. 2000; Wang et al. 2007) and CW**	2
	30	0.24	(Xu et al. 2000; Wang et al. 2007)	187	285	Estimated from (Xu et al. 2000; Wang et al. 2007) and CW**	1,2
	15	0.24	(Anusavice 2003; Pest et al. 2006; Powers & Skaguchi 2011)	125	285	ParaCore (CW**)	1,2
Post	207	0.3	Stainless steel post (Rodríguez-Cervantes et al. 2007; Plotino et al. 2007; Stewardson et al. 2010)	1436	1436	(Plotino et al. 2007)	1
	48	0.3	N/A	1200	340	N/A	2
	30	0.3	ParapostFiber White (CW**)	1200	340	ParapostFiber White (CW**)	1,2
	12	0.3	N/A	1200	340	N/A	2

* IV: Ivoclar Vivadent, AG, Schaan, Liechtenstein

** CW: Coltene Whaledent

Table 4. ANOVA on overall safety factor (SF) for the first virtual test

Source	Type III Sum of Squares	df	Mean Square	F	p>F
Corrected model	8.404[a]	7	1.201	226.574	.000
Intersection	416.988	1	416.988	78695.158	.000
D_{p2}	.769	1	.769	145.142	.000
L_{pr}	.097	1	.097	18.379	.000
E_{post}	7.403	1	7.403	1397.049	.000
E_{core}	.000	1	.000	.085	.770
E_{crown}	.000	1	.000	.040	.841
r_d	.001	1	.001	.217	.642
r_c	.133	1	.133	25.105	.000
Error	1.992	376	.005		
Total	427.384	384			
Corrected total	10.396	383			

a. R Squared = .808 (Adjusted R Squared = .805)

Table 5. Mean and standard deviation of overall safety factor at two levels of E_{post}

Source	N	SF (Mean)	SF (Deviation)
E_{post} = 30 GPa	192	1.18	0.23
E_{post} = 207 GPa	192	0.90	0.12
Total	384	1.04	0.16

Table 6. ANOVA on overall safety factor (SF) for test 1 (only cases with E_{post}=30 GPa)

Source	Type III Sum of Squares	df	Mean Square	F	p>F
Corrected model	.003[a]	6	.000	6.324	.000
Intersection	89.467	1	89.467	1271873.540	.000
D_{p2}	.000	1	.000	4.715	.034
L_{pr}	1.416E-5	1	1.416E-5	.201	.655
E_{core}	.002	1	.002	21.720	.000
E_{crown}	.001	1	.001	8.612	.005
r_d	5.1666E-5	1	5.1666E-5	.734	.395
r_c	.000	1	.000	1.959	.167
Error	.004	57	7.034E-5		
Total	89.474	64			
Corrected total	.007	63			

a. R Squared = .400 (Adjusted R Squared = .336)

Table 7. ANOVA on overall safety factor (SF) for test 2

Source	Type III Sum of Squares	df	Mean Square	F	p>F
Corrected model	8.823[a]	8	1.103	287.532	.000
Intersection	264.438	1	264.438	68942.320	.000
E_{post}	.019	2	.009	2.421	.091
E_{core}	.026	2	.013	3.355	.037
E_{crown}	8.765	2	4.382	1142.540	.000
D_{p2}	.014	2	.007	1.812	.166
Error	.898	234	.004		
Total	274.159	243			
Corrected total	9.721	242			

a. R Squared = .908 (Adjusted R Squared = .905)

Figure 1. Sagittal section of the geometrical model and the modelled components. Geometrical parameters of the restoration and loading angle considered

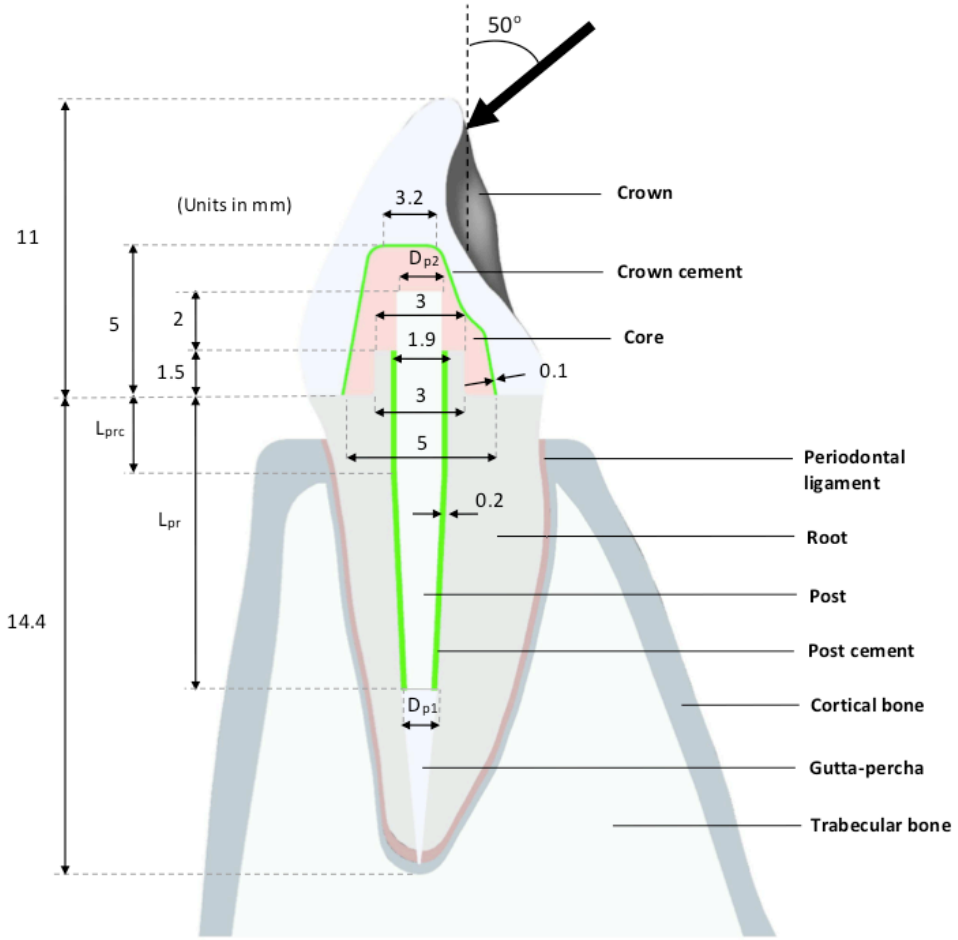

Figure 2. Boxplot of components safety factor in test 1

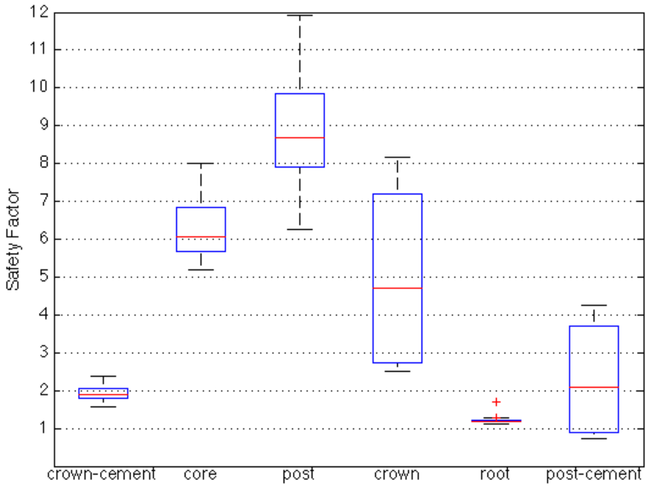

Figure 3. Representation of the safety factor (post not displayed) in test 1 when E_{post}=30 GPa (a) and E_{post}=207 GPa (b) and equal values for the rest of parameters (E_{crown}=62 GPa, E_{core}=15 GPa, L_{pr}=7 mm, D_{p2}=1.2 mm). The location of critical point marked with asterisk.

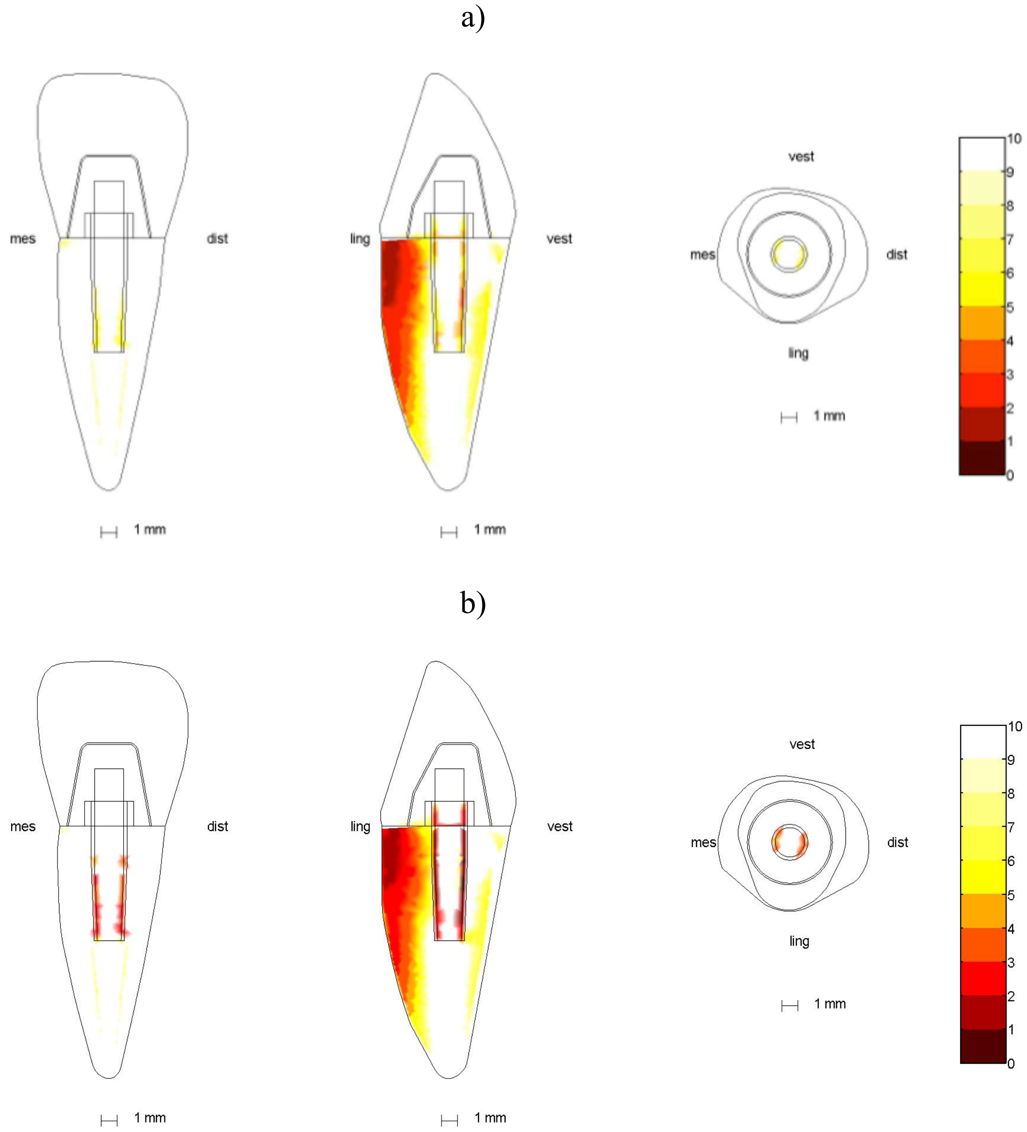

Figure 4. Representation of the safety factors (post not displayed) in test 2 when E_{crown}=124 GPa (a), E_{crown}=62 GPa (b) and E_{crown}=30 GPa (c) and equal values for the rest of parameters (E_{post}=30 GPa, E_{core}=15 GPa, L_{pr}=7 mm, D_{p2}=1.2 mm). The location of critical point marked with asterisk.