Two-Dimensional FEA of Dowels of Different Compositions and External Surface Configurations

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Abstract

Purpose: The degree of stress generated in the endodontically treated and restored tooth can be influenced by the composition and configuration of the dowels used for the restoration. Using two-dimensional (2D) finite element analysis (FEA), this study tested the hypothesis that the characterization of the stress distribution can be influenced by which evaluation method is employed: protrusion loading and 4-point flexural strength test or varying the type of material (carbon and glass fiber) or the external configuration of the dowel (smooth and serrated).
Materials and Methods: For simulation of the protrusion load test, models were generated with Mechanical-AutoCAD V6 software from an image of an anatomical plate, one maxillary central incisor, and two dowels and exported to Ansys 9.0. The bone region model was fixed, and a tangential load of 1 N with a 135° inclination to the tooth longitudinal axis was applied at the level of the palatal surface of the crown. In the simulation of a 4-point flexural strength test, a 1 N perpendicular load was applied in two points to the dowel. The dental materials and structures were considered elastic, isotropic, homogeneous, and linear, with the exception of the dowel, which was assumed to exhibit orthotropic behavior. Mechanical properties were defined based on a review of the literature, and the model was meshed with an eight node tetrahedral element.
Results: The stress results from both tests were analyzed according to von Mises criteria and principal stresses (Sx). Data from the 4-point flexural strength test simulation showed that, for the serrated dowels, a higher stress concentration was found; however, no difference in the occlusal load for material or dowel configuration was found.
Conclusions: These results suggest that although the external configuration of the dowel influences direct loading, when the dowel is integrated to the tooth and setting material, the influence on biomechanical behavior disappears.

In current restorative therapy, clinicians strive to preserve any tooth, even if great destruction exists, and varying dowel systems have been proposed for restoration of devitalized teeth.[1,2] The essential function of the dowel is to retain the material applied for tooth restoration.[3] Concerning stress distribution in the restored tooth, restoration procedures should provide a biomechanical balance to the dental structure with the restorative material presenting mechanical behavior similar to that of sound tooth structure.[4,5] Some studies have concluded that the attributes of carbon and glass fiber dowels make them suitable for dowel restoration.[3,6] Some manufacturers state that carbon and glass fiber dowels have a transverse elastic modulus close to that of dentin and are therefore less likely to cause damage to the restored tooth. Additionally, fiber dowels and resin composite have a Young's modulus similar to that of dentin, thus enabling the transference of occlusal stress from the restoration to the tooth structure.[6,7] Clinical[8,9] and in vitro studies[10] have demonstrated that such characteristics result in a reduction of the incidence of root fracture. Conversely, teeth restored with stainless steel dowels have been shown to present a higher incidence of longitudinal root fracture, because stresses are concentrated along the dowel–core interface.[7]

The influence of dowel length, size, and design on the biomechanics and stress distribution of restored teeth has been reported.[7] The design may vary in shape, including parallel-sided or tapered, and in surface characteristics, such as smooth or serrated forms. Under tensile load, core retention is significantly improved when a serrated dowel is used, but the smooth dowel has demonstrated significantly greater rigidity, as the serrations are detrimental to the fiber integrity.[11]

The influence of dowels on tooth structure has been investigated in laboratory tests, with results differing depending on the way in which the load is applied: directly on the dowel[2,12] or on the dowel in association with dental structures.[1,11] This difference in methodology is of great importance, because when results of studies are compared, the differences in the methodologies may not be taken into account.

The analysis of the effect of different types of dowel on the mechanical performance of restored teeth using the finite element model has been validated by experimental results.[7,13] In this study, the finite element method was used to evaluate stress distribution on maxillary central incisors restored with varying dowel systems. The restored tooth numerical models were submitted to load in a protrusion simulation, and the dowel numerical models were submitted to a 4-point flexural strength test. Using finite element analysis (FEA), this study tested the hypothesis that the characterization of the stress distribution can be influenced by which evaluation method is employed: protrusion loading and 4-point flexural strength test or varying the type of material (carbon and glass fiber) or the external configuration of the dowel (smooth and serrated).

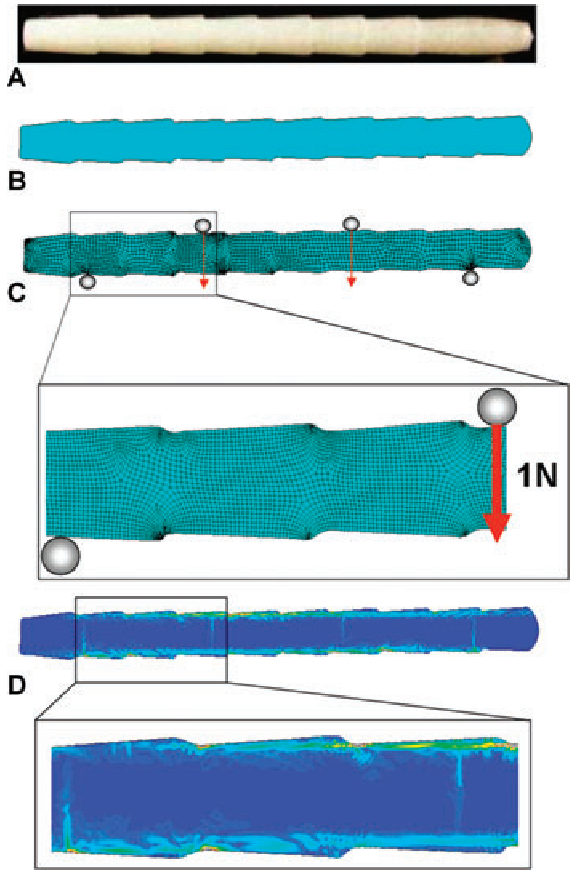

Figure 1 Two-dimensional numerical model generation from dowels: (A) image of a serrated dowel; (B) plotted area on finite element software (Ansys 9.0); (C) mesh created by mechanical properties of each structure and load application simulating 4-point flexural test; (D) stress levels and concentrations by von Mises criteria.

Materials and methods

A linear static structural analysis using two-dimensional (2D) FEA was performed with the load applied obliquely to a tooth-dowel-ceramic complex and directly to the dowel in a 4-point flexural strength test using a glass-fiber (Reforpost Glass Fiber dowel, Ângelus, PR, Brazil) and a carbon fiber dowel (Reforpost Carbon Fiber dowel, Ângelus). Results of the 2D FEA were examined for the occurrence of high von Mises stress levels and/or stress concentrations that might predict problems for the clinical success of such systems.

Numerical models for 4-point flexural strength test

Bidimensional numerical models were obtained from digital images of the dowels (Fig 1). The geometry was determined and established using the Mechanical Desktop AutoCAD V6 (Autodesk, Madrid, Spain) program. Four models were created: smooth glass fiber dowel (Experimental Glass Fiber Dowel, Ângelus), smooth carbon fiber dowel (Experimental Carbon Fiber Dowel, Ângelus), serrated glass fiber dowel (Reforpost Glass Fiber Dowel), and serrated carbon fiber dowel (Reforpost Carbon Fiber Dowel, Ângelus). The resulting files were then exported to Ansys 9.0 (Ansys, Inc., Houston, TX) using IGES format (Initial Graphics Exchange Specification), and the areas corresponding to dowel structure were plotted (Fig 1) and meshed with isoparametric elements of eight nodes with 3 degrees of freedom per node (PLANE 183). The glass and carbon fiber dowels were considered orthotropic, as they present different mechanical properties along the fiber direction (x direction) and along the other two normal directions (y and z direction). In Table 1, Ex, Ey, and Ez represent the elastic modulus in the three directions, while ηxy, ηxz, and ηyz and Gxy, Gxz, and Gyz are, respectively, the Poisson's ratios and the shear moduli in the orthogonal planes (xy, xz, and yz). Because this study used a 2D model, the same value was assumed for the y and z normal directions. Mechanical properties for the orthotropic materials were obtained from a review of the literature (Table 2). The values for those considered isotropic are listed in Table 2. To simulate the 4-point flexural strength test for the dowels, two perpendicular static loads (1N) with a 15-mm distance between them were applied (Fig 1). Model movements were restricted at the inferior face with two points at a 5-mm distance from each

Table 1 Mechanical properties of glass and carbon fiber dowels

Properties*	Carbon fiber dowel	Glass fiber dowel
Ex (MPa)	118,000	37,000
Ey (MPa)	7200	9500
Ez (MPa)	7200	9500
ηxy	0.27	0.27
ηyz	0.27	0.27
ηxz	0.34	0.34
Gxy	2.80	3.10
Gyz	2.80	3.10
Gxz	2.70	3.50

*Mechanical properties obtained from De Santis et al,[14] Ferrari et al,[15] and Asmussen et al.[16]

E = elastic modulus; η = Poisson's ratio; G = shear modulus; x,y,z = specific orthogonal plane directions.

Table 2 Mechanical properties of dental structures and materials

Strucuture	Young's modulus (MPa)	Poisson ratio	References
Trabecular bone	1370	0.30	17
Cortical bone	13,700	0.30	17
Periodontal ligament	68.9	0.45	17
Dentin	18,600	0.31	17
Gutta-percha	0.69	0.45	17
Pulp	2	0.45	18
Resin luting cement	5100	0.27	14–16
Composite resin	16,600	0.24	19
Feldsphatic Ceramic	69,000	0.30	14–16

extremity. Qualitative analysis was performed by the stress distribution according to von Mises criteria and principal stresses in the Sx direction (Fig 1). The graphic quantitative analysis was performed from a line perpendicular to and in the midpoint of the dowel.

Numerical models and 2D FEA of restored teeth

An intact maxillary central incisor was prepared with a chamfer cervical termination, 1-mm axial depth and 2-mm incisal reduction. The tooth was restored with feldspathic porcelain. Then, the tooth was cut longitudinally in the mesiodistal direction, and a digital image was obtained. From this image, a simulation was made of the endondontic treatment and restoration using a nonmetallic dowel, composite core, and feldspathic porcelain. From the anatomic plate, the distances of each anatomic structure followed the normality pattern shown in the literature (Fig 2).

Following the protocol of image processing (Fig 2) described for dowels, five 2D numerical models of the restored maxillary incisor were created: vital and restored; endodontically treated and restored with smooth glass fiber dowel; endodontically treated and restored with smooth carbon fiber dowel; endodontically treated and restored with serrated glass fiber dowel; and endodontically treated and restored with serrated carbon fiber dowel. Materials used for core, crown, and luting agent were, respectively, composite resin, 2-mm-thick feldsphatic porcelain, and 100-μm-thick resinous cement. For the restored tooth numerical models, all structures and materials used were considered isotropic, elastic, linear, and homogeneous (Table 2), except the glass and carbon fiber dowels, which were considered orthotropic (Table 1). Particular attention was employed in the refinement of the mesh resulting from convergence tests at the cement layer interfaces (Fig 2). To simulate adhesion between the structures, all interfaces (ceramic–resin cement, resin cement–composite core, composite core–dowel, dowel–resin cement, and resin cement–dentin) were considered completely bonded. A static and oblique (135°) load of 2 N in intensity was applied at the lingual face (Fig 2), simulating contact with the mandibular incisors in the protrusion movement. Model movements were restricted at the external lateral outline and base of the bone structure in all directions. Qualitative analysis of the stress distribution was performed in accordance with the von Mises criteria (Fig 2). Quantitative analysis of stress distribution was performed by measuring stresses at specific points located in a line created from the point of load application to the buccal alveolar process. The direction of application was based on studies of fracture pattern analysis of the materials tested.[20,21]

Results

The 2D FEA of models from the 4-point flexural strength test showed that the serrated dowels presented higher stress concentration than smooth dowels (Fig 3). The serrated dowel showed tensile stress levels of about 150 MPa, while smooth dowels showed tensile stress levels about of 75 MPa (Fig 4); however, no difference was observed relating to dowel composition (Figs 3 and 4).

In the restored tooth, irrespective of the dowel material or design, there was no difference in the stress distribution (Figs 5 and 6). The 2D FEA images showed that the use of dowels resulted in stress distribution along the root similar to that found in the tooth restored with feldspathic porcelain, except with a higher stress concentration at the buccal face of the root, but without significant stress concentration in the dowels.

Discussion

Because the stress distribution results were influenced by the evaluation method, the hypothesis that stress distribution findings will be influenced by the method used to apply the load was accepted. Although carbon fiber dowels afford a 3× higher modulus of elasticity[15] and greater flexural strength[22] than glass fiber dowels, no difference between them in stress distribution was found when the tooth-restoration complex was evaluated. Neither the composition nor the configuration of the dowel influenced the stress distribution under the test conditions (Fig 5). This behavior could be due to the formation of a single structure provided by adhesive cementation of the nonmetallic dowel in the root canal[23,24] and to the similarity in mechanical behavior among dental structures and restorative materials.

Varying stress distribution was related to dowel configuration with stress concentration in the serrations, when the load was directly applied in the dowel. That stress distribution pattern

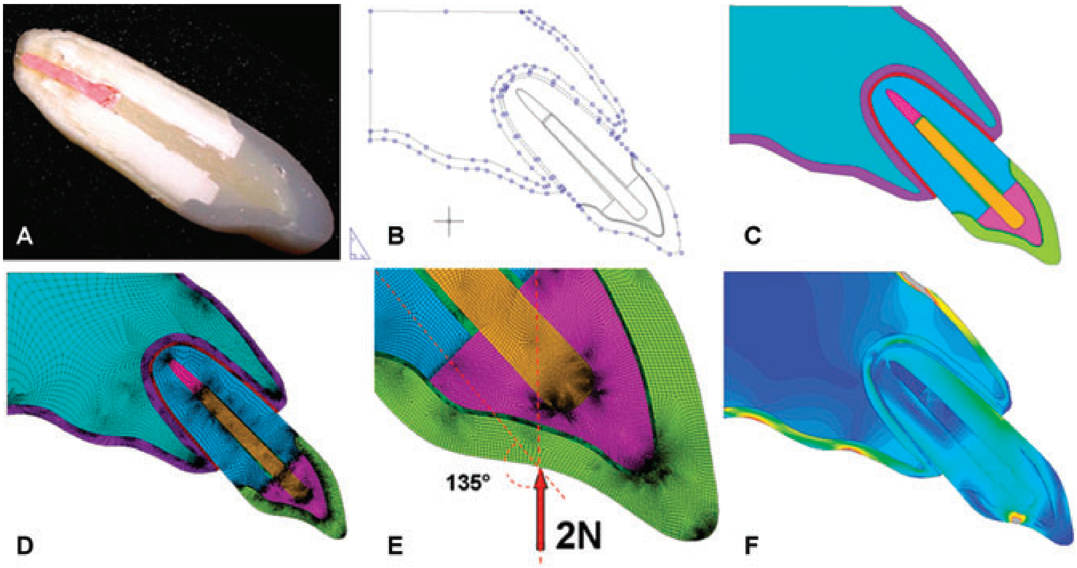

Figure 2 Two-dimensional numerical model generated from restored tooth: (A) longitudinal slice of endontically treated and dowel-core-crown restored tooth; (B) external and internal contour obtained by anatomical plate-Mechanical Auto CAD (Desktop); (C) plotted areas on finite element software (Ansys 9.0); (D) mesh created by mechanical properties of each structure; (E) load application on lingual face; (F) stress levels and concentrations by von Mises criteria.

was null, however, when the dowel was associated with other restorative materials (Fig 3). This comparison is of clinical importance because many clinicians regard the flexural strength of dowels as the only reference for restorative procedures.

A previous study reported that the differences in the external configuration of fiber dowels directly influenced the rigidity and retention of the core material, with higher retention values found for serrated dowels than with smooth dowels and the 3-point flexural strength test showing significant differences in the values of relative rigidity for smooth dowels (3.8 ± 0.46), while serrated dowels presented premature fractures and a relative rigidity of 1.7 ± 0.07.[11] These results corroborate the stress distribution findings observed related to dowel serrations (Fig 5). Serrated dowels, which are composed of discontinuous fibers,[11] presented higher retention values and lower values of relative rigidity than smooth dowels. On the other hand, the stress distribution under 2D FEA was similar for both serrated and smooth dowels. Additional studies associating destructive

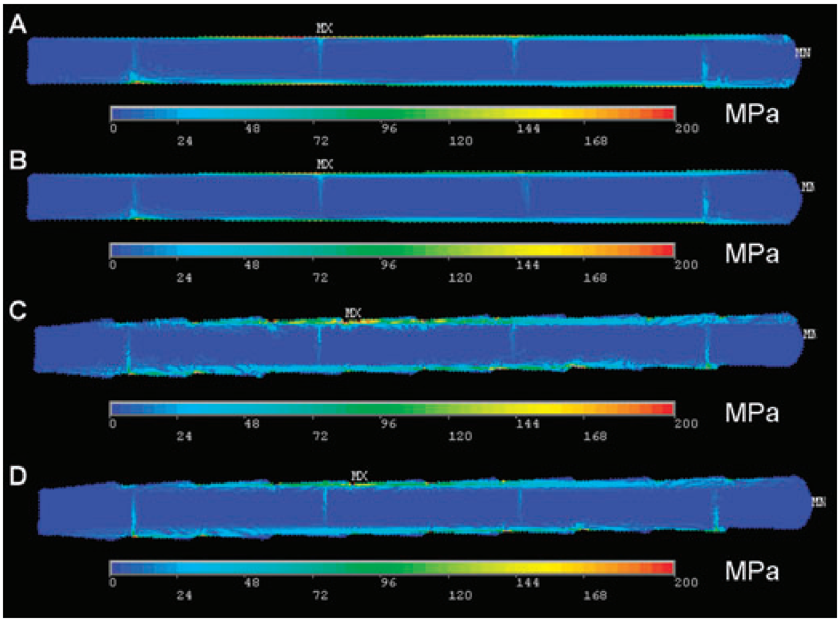

Figure 3 Stress levels and concentrations in 4-point flexural test simulation using von Mises criteria: (A) smooth carbon fiber dowel; (B) smooth glass fiber dowel; (C) serrated carbon fiber dowel; (D) serrated glass fiber dowel.

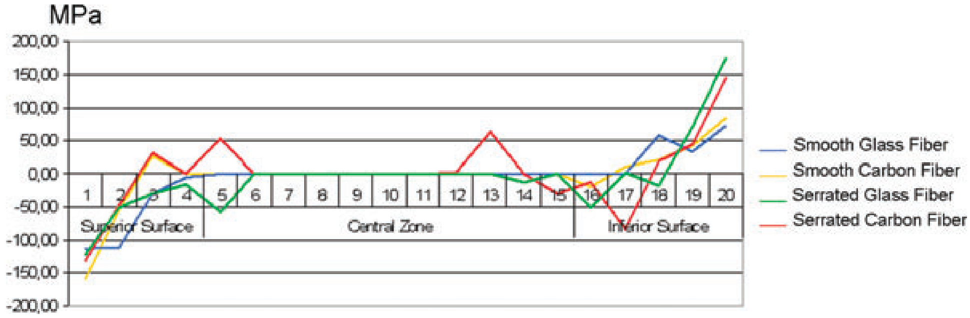

Figure 4 Quantitative analysis of stress levels and concentrations on dowels using Sx criteria.

and nondestructive tests should be performed to better elucidate the influence of the fiber discontinuity of serrated dowels on their mechanical behavior.

In addition to the qualitative analysis of stress distribution based on a color scale, a quantitative analysis was performed using graphics of stress values from von Mises criteria for the tooth-restoration complex and stress values from the dowel Sx direction. Twenty-six points of quantitative analysis were selected, with equal difference among them, from all structures involved at the tooth restoration complex model, giving greater

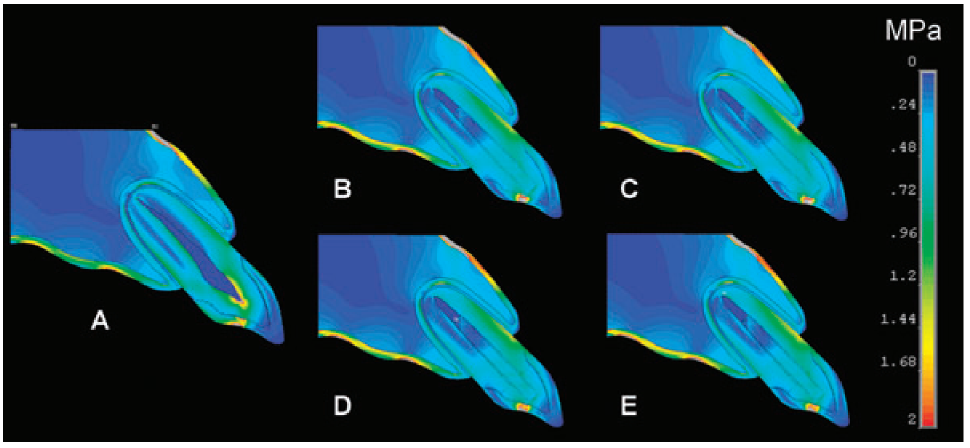

Figure 5 Stress levels and concentrations in the tooth-restoration complex using von Mises criteria: (A) restored maxillary incisor; (B) smooth carbon fiber dowel; (C) smooth glass fiber dowel; (D) serrated carbon fiber dowel; (E) serrated glass fiber dowel.

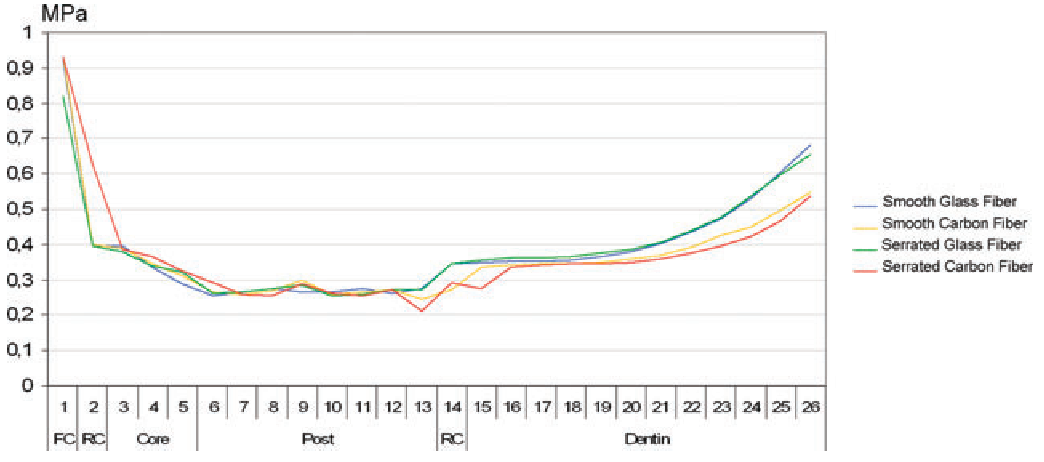

Figure 6 Quantitative analysis of stress levels and concentrations in the restored tooth using von Mises criteria (FC = feldsphatic porcelain; RC = resin cement).

attention to dowel and dentin structures. The dowel model was essentially divided into three regions—superior and inferior surfaces and central zone—with 20 points with equal difference among them. Quantitative analysis using the von Mises criteria found results similar to those found with the qualitative analysis. Tests showed no difference relating to the dowel material, but varying the external configuration showed a difference in the flexural test.

Figure 6 illustrates the fact that the stress distribution was similar among the groups and that a tendency to a higher stress concentration in dentin could be noted in the teeth restored with glass fiber dowel, irrespective of the external configuration. Dowel composition influenced the stress distribution at the point of load because of the difference in the fiber elasticity modulus in the X direction (Fig 4). In the load opposite surface, the external configuration significantly influenced the stress distribution, because the areas of stress concentration were located more distant from the load point.

The way in which the load was applied in this study, simulating a protrusion movement, might be considered a limitation in comparison to clinical conditions in which the load is intermittent and results in a fatigue process. The use of 2D numerical models also limited the analysis, as the stress distribution in the Z direction could not be assessed. On the other hand, the numerical model was generated with meticulous attention to the simulation of anatomical structures in their real proportions, including the periodontal ligament and cortical and trabecular bone. In contrast to other studies,[25,26] simulation of the cementation layer around the dowel was seen as important so as to better evaluate the stress distribution among structures with varying moduli of elasticity. In the oblique loading simulated in this study, dowel flexural behavior must be carefully considered because of its direct influence on stress distribution.[27] Thus, the angulation of load application followed that of 135° as in the clinical situation,[6,28] and dowels were considered orthotropic, because they present different mechanical properties in the X and Y directions, and their mechanical behavior differs in relation to the direction of the main maximum stresses (Sx and SY).

This study had limitations, such as 2D FEA. The analysis by finite elements using 3D numerical models is suggested. Suggestions for future studies include biomechanical behavior analysis by experimental methods such as strain gauge and 4-point flexural strength tests. Another suggestion is to investigate factors that influence biomechanical behavior, such as different load points and different restorative materials.

While the specific analysis referent to material and configuration presents relevance for mechanical analysis between the dowels employed, the principal finding of this study was to demonstrate the necessity of analyzing the characteristics of methodologies used during comparisons of the results of different studies.

Conclusions

Within the limitations of this in vitro study, the following conclusions were drawn:

The fiber dowel composition did not influence biomechanical behavior of 4-point flexural strength and the restored tooth model; however, the external configuration of the dowel influenced the direct loading applied in the 4-point flexural strength test. When the dowel was integrated with the tooth-restoration complex, the external configuration did not influence biomechanical behavior. Thus, when comparing results from different studies, differences in the methodology used must be taken into account.

Acknowledgments

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