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Finite Element Analysis of Biomechanical Behaviour of Remaining Coronal Dentin in Endodontically Restored Tooth - A Systematic Review [Evaluation of Stress Distribution in FEA Studies]

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Background: Since few years finite element (FE) analysis has turn out to be a widespread tool for investigators seeking to simulate the tooth biomechanics and associated structures. Finite element method plays important role to expand understanding of the ferrule effect. This paper contains a systematic review and conclusions from FE method grounded computational simulations of the the tooth with post and core to simulate function and tissue behavior

Methods: 14 applicable papers were linked within this systematic literature search. Uprooted data contained information on type of tooth, location of tooth, magnitude of force, software used for modelling, boundary condition, method of scanning, validation, tooth with ferrule, tooth without ferrule, key findings.

Results: Included papers illustrated use of FE analysis for replication of including nonlinear tooth and tissue mechanics, contact analysis and rigid body movements. We executed multi-database systematic review through PRISMA standards accomplishing inclusion criteria and results were investigated and précised for appropriate papers.

Discussion: With prompt expansions of computer knowledge, the FEA now recognized as a potent

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method in dental biomechanics due to its flexibility in measuring stress dispersals within multidimensional structures. The researcher will be well equipped to understand the results of FEA investigations and correlate these results to clinical settings after learning the basic theory, application, method, and limitations of FEA in dentistry. Ferrule has a precarious impact on stress reduction. Teeth are less stressed when posts and cores are composed of strong materials. Keeping supragingival tooth structure included within the crown gives repaired teeth extraordinary strength.

Keywords: Ferrule; post and core; finite element analysis.

1. INTRODUCTION

The power of tooth is directly interrelated to the extent of residual tooth configuration. Therefore conservation of tooth configuration is vital in successful treatment of mechanically compromised pulpless teeth [1]. A ferrule can offer protective strengthening to pulpless teeth by encapsulation of residual coronal structure and by repelling functional lever forces while mastication. Ferrule height minimum around 1 to 2 mm is necessary to achieve such shielding effect [2]. Latest clinical research reported that the ferrule structure has direct impact on clinical achievement rate of pulpless teeth [3]. This method encompasses a series of computational measures which estimate the strain and stress within a structural model triggered by thermal change, external force, magnetic field and other several factors. This technique is very beneficial in assessing the biomechanical appearances of dental prostheses and associated oral tissues which are challenging to investigate in vivo. The stress expected through structural model can be scrutinized using software within the FE background to estimate diversity of physical considerations [4]. Outcome of a prosthesis may be subject to on how the stress is scattered to the tooth configuration therefore it is obligatory to research the stress dispersal form which can be subjective to the existence or absence of ferrule.

The outcomes from FE analysis grounded computational simulations of the tooth with post and core to model function and tissue performance are summarized in this publication.

2. MATERIALS AND METHODS

Original research publications using FE models of the tooth restored with post and core to reproduce function and tissue behavior were shortlisted. Also, studies using FE analysis to investigate role of ferrule to improve mechanical durability were suitable for inclusion. Abstracts were selected and applicable articles recorded for full text review. If full-text papers met the inclusion criteria, they were considered complete.

2.1 Search Strategy

We executed a systematic review, searching PubMed, Medline and Elsevier (ScienceDirect) for applicable peer-reviewed articles with English-language abstracts published based on these keywords: (“ferrule” OR “coronal dentin”) AND (“finite element” OR “FEM” OR “computer simulation” OR “stress distribution”). Reference lists of applicable publications were also appraised to evade missing applicable articles.

PICO elements were labelled first to express inclusion and exclusion criteria. (P) Endodontically repaired teeth with ferrule (I) compared with teeth lacking ferrule (C) result in more favourable stress dispersal within tooth interfaces (O).

2.2 Inclusion Crtiteria

Two reviewer assessed and selected the study on the basis of following inclusion crieteria, 1) investigating stress distribution within root post and core restored tooth with ferrule present or absent by means of finite eleent analysis. 2) Full-text article published only in English language 3) Providing detailed data of each group and subgroup.

Studies were excluded if they were 1)not related to ferrule effect. 2) Not done by mean of finite element analysis. 3) Not providing detailed data of each group and subgroup.

The applicable papers related to biomechanical behaviour of pulpless teeth were considered.

Table 1. Characteristics of the Included Studies

Sr no.	Ref	Year of publication	Country of publication	Study type	Method of scanning	Modelling software	Fea software	Type of tooth	Type of loading	Validation
1	**Beata et al**[5]	2013	Poland	3D FEA	3D laser Dental Scanner D250 (3ShapeA/S) a CT scan of the tooth XCB-500/I-CAT		ANSYS 14	maxillary first incisors	100 N cingulum, at 130◦ to the longitudinal axis	No validation
2	**Chen et al**[6]	2014	china	3D FEA	3D scanner (3DX Multi-Image Micro CT)	Mimics software v10.0 (Materialise	Ansys v10.0	maxillary canine	5 degrees angle, 300-N load at 3.0 mm under the cusp lingual surface of the prosthesis	No validation
3	**Mahmoudi et al** [7]	2017	Iran	3D FEA	By using mounted tooth section with a digital camera (IXY30S; Canon)	SolidWorks; Dassault Systèmes SolidWorks Corp	Abaqus/CAE; Dassault	mandibular first premolar	200 N, 45 degrees angle to occlusal plane	No validation
4	**Liu et al**[8]	2014	China	3D FEA	scanning an acrylic resin tooth replica.	UG NX 6.0; Ansys	ANSYS 10.1	maxillary premolar	a 200-N oblique static load angled at 45 degrees	No validation

Sr no.	Ref	Year of publication	Country of publication	Study type	Method of scanning	Modelling software	Fea software	Type of tooth	Type of loading	Validation
5	**Roscoe et al**[9]	2013	Uberlandia	3D FEA	DT3D database	Rhinoceros 3D, Seattle, Wa	NeiNASTRAN software; Noran Engineering Inc, Westminster, Calif	maxillary canine	100 N load Angle of 15-degree to the long axis of the tooth	validation experiment included in protocol
6	**Watanabe et al**[10]	2012	Brazil	3D FEA	computed microtomography images (μCT),	SolidWorks Corp., Concord, MA	ANSYS Workbench	maxillary central incisor	180 N, on the incisal third, palatal surface 45 degree to its long axis	No validation experiment included in protocol
7	**Verri et al**[11]	2017	Florida	3D FEA	CT scan software InVesalius (Renato Archer Research Center, Campinas, Sao Paulo, Brazil)	FEMAP 11.1.2 software (Siemens PLM Software Inc., Santa Ana, CA, USA). Model Refinement in Rhinoceros 3D 4.0 (NURBS Modeling for Windows, Seattle, WA, USA)	NEiNastran 11.0 software (Noran Engineering, Inc., Westminster, CA, USA	maxillary central incisor	oblique loading to the palatal surface , 45 degree to its long axis, with 100 N force	No validation experiment included in protocol
8	**Upadhyaya, et al**[12]	2015	India	3D FEA	3D MAX software	3D MAX (Autodesk Foundation, CA, USA	ANSYS version 10.0 (Swanson Analysis Inc., Houston,	maxillary central incisor	A load of 100 N was applied to the lingual surface 2 mm above the incisal	No validation experiment included in protocol

Sr no.	Ref	Year of publication	Country of publication	Study type	Method of scanning	Modelling software	Fea software	Type of tooth	Type of loading	Validation
							Tx, USA		edge at a 45° angle.	
9	**Ausiello et al [13]**	2017	Italy	3D FEA	a micro-CT scanner system	ScanIP®3.2 module software (Simpleware Ltd.) Bruker microCT, Kontich, Belgium	HyperWork®14.0 (Altair EngineeringInc.)	canine	On the lingual surface, 50 N was applied at a 45-degree angle to the tooth's long axis.	No validation
10	**Santos-Filho et al**[14]	2014	Brazil	3D FEA	CAD software was used to import the *.STL files that were produced.	Rhinoceros©5.0 Computer Assisted Engineering software, Femap 10.1; Velocity Series, Siemens PLM Software, Plano, TX CAD Rhinoceros 3D 4.0; McNeel North America, Seattle, WA	(NEi Nastran 9.2; Noran Engineering, Westminster, CA),	maxillary central incisor.	A 100 N force was applied at a 135 degree angle to the tooth's long axis.	No validation
11	**Rodrigues et al**[15]	2017	Uberlandia	3D FEA	interactive medical imaging software	3-Matic 8.0, Materialise Mimics 16.0; Materialise, Leuven,	MSC.Marc/MSC.Mentat	maxillary central incisor	155-N vertical force .	validation experiment included in protocol

Sr no.	Ref	Year of publication	Country of publication	Study type	Method of scanning	Modelling software	Fea software	Type of tooth	Type of loading	Validation
						Belgium. MSC.Patran 2010(MSC Software, Santa Ana, CA)				
12	**Zhang et al**[16]	2014	China	3D FEA	The laser-assisted 3D digitizing system	D800, Wieland Dental & Technik GmbH & Co. KG, Schwen- ninger, German ScanIP1 module (Simpleware Ltd, UK).	ABAQUS/CAE (SIMULIA, Version 6.10, Providence, RI, USA	maxillary right central incisor	350 N load ,45 angle degree with long axis of the tooth.	validation experiment included in protocol
13	**Juloski et al[17]**	2014	*Italy*	3D FEA	3D laser-based digitizing software (Cyberware , Inc., Monterey, California, USA)	3D parametric solid modeler (Pro-Engineering 16.0 Parametric Technologies, USA). 3D CAD (Auto-cad 12, Autodesk Inc.)	ANSYS rel. 9.0 (Ansys Inc.Houston	maxillary first premolar	200 N load on the buccal cusp, 45◦ to the longitudinal axis of the tooth	validation experiment included in protocol
14	**Rajambigai et al**[18]	2016	india	3D FEA	modeled with geometric data	PRO Engineer software (Parametric Technology Corporation, USA).	ANSYS WORKBENCH 10.0software	maxillary central incisor	A 100 N load is applied at a 45o angle to the tooth's long axis. .	No validation experiment included in protocol

Table 2. Clinical findings

Sr.no.	Authors	Study variables	Conclusion
1	Beata et al	The influence of the ferrule and length of cast post and cores, as well as FRC posts, on the biomechanical integrity of anterior teeth was investigated. The study looked at the strength of dental tissues, ceramics, and composites, using the Tsai-Wu criterion for FRC and the von Mises criterion for cast Ni Cr alloy.	The effect of ferrules in teeth is that they reduce stress in the post-dentin and luting cement. Tensile stresses around posts with ferrule effects were 1.7–3.0 times lower than those around teeth without ferrules. In comparison to FRC posts, cast posts restored teeth had better stress dissipation. Teeth are less stressed when posts and cores are composed of hard materials.
2	Chen et al	The stress dissipation in the post-core system and root structure of a maxillary canine with various ferrule configurations was examined in this study. By placing a 300 N load to the middle of the prosthesis's lingual surface, Von Mises stresses were determined.	The von Mises stress in the zirconia post and the post-dentin interface is lowered when ferrule height is increased. When the ferrule height was increased from 0 to 3 mm, the maximum von Mises stress in the mid and apical regions of the root was reduced.
3	Mahmoudi et al	An inhomogeneous post was tested to see if it may lower dangerous stresses in the dentin and at the interfaces. A 3-D model of a post-core treated first premolar tooth with and without a ferrule was created. The stress at the dentin-adhesive contact was evaluated to assess the risk of adhesion loss.	The ferrule's presence lowered the pressures at the interface. Except for the carbon fibre post, the stresses at the post cement were greater than the stresses at the crown cement in all models without a ferrule.
4	Liu et al	Study analyzed the biomechanical behavior of maxillary premolars with dissimilar ferrule designs and to explore the influence of cusp inclination and occlusal contact on stress dispersal. Five 3 models with different ferrule design, cuspal angulation and loading condition evaluated for stress dispersal in the form of von Mises stress.	According to the findings, maxillary premolars with enduring facial dentin demonstrate progressive local stress on the root section of the dentin. Local strains can be reduced by shifting the loading location and lowering the face cusp inclination
5	Roscoe et al	The impact of alveolar bone loss, post type, and ferrule presence on the biomechanical behaviour of endodontically treated maxillary canines was studied by a researcher. For a better understanding of the failure criterion, researchers used a mix of strain monitoring and finite element analysis. For stress dispersal, the models were examined using the greatest primary stress criteria.	The presence of a ferrule improved the mechanical behaviour, according to the findings. The absence of a ferrule increased the buccal and proximal strain values significantly.
6	Watanabe et al	Researcher investigated the impact of ferrule height (0, 1, and 2 mm) on the tooth structure. FE software was used to determine the equivalent von Mises	The greatest primary stress, concentration in all structures of models, was seen to condense as ferrule size increased. Teeth that lack a ferrule are more likely

Sr.no.	Authors	Study variables	Conclusion
		stress, maximum principal stress, minimum principal stress, and shear stress within different regions of the tooth structure.	to develop fractures in the apical root third.
7	Verri et al.	The biomechanical behavior of a tooth rehabilitated with metal-free crowns put in teeth with no coronal structure was studied while the number of posts employed was varied. Non-ductile elements having a higher chance of fracture were calculated using the maximum primary stress.	In teeth with no surviving tooth structure, glass fibre posts cause less stress along the post but more stress in the simulated tooth region, potentially jeopardizing restorative durability.
8	Upadhyaya, et al	Using finite element analysis, the researchers looked at how the design and material of a post with or without a ferrule affected stress dispersal.Twelve 3D models of post retained central incisors with and without ferrule, different post material were completed. Results were investigated using 3D von Mises criteria.	Ferrules enable homogeneous stress distribution and reduce cervical strains, according to the findings of the study.
9	Ausiello et al	The mechanical behavior of post-restored canine teeth was investigated using a ferrule design with specified post material shape combinations. Finite Element (FE) Analysis was used to examine four models: with and without a ferrule for both types of post material and form. As a measure of possible harm, the maximum normal stress criteria were used.	According to the findings, models without a ferrule had higher stresses (16.3 MPa) than those with a ferrule (9.2 MPa). Stress was uniformly distributed over the abutment and the root with a ferrule, with no dangerous stress concentration.
10	Santos-Filho et al.	The effect of the post system, length, and ferrule on the biomechanical behavior of root-treated anterior teeth was studied. The von Mises criterion was used to evaluate the results.	Regardless of the post system, the inclusion of a ferrule increases the fracture resistance of endodontically treated teeth. The strain, fracture resistance, and fracture pattern were all determined by ferrule.
11	Rodrigues et al.	Using 3D FEA, researchers tested the influence of ferrule designs on both glass fibre posts and all-ceramic restorations (CAD-CAM) on both maxillary central incisors. During bite force recording for FEA validation, strain gauges were employed to detect ceramic strain. For stress evaluation, modified von Mises equivalent stress was used.	The stress analysis study found that retaining the coronal structure in root-treated teeth is important, and that increasing ferrule height across the full root circumference improves stress dispersal. The lack of a ferrule in the proximal region resulted in higher stress levels in the root dentin and root canal.
12	Zhang et al	Using extended finite element analysis (XFEM) and fracture failure testing, researchers assessed the fracture resistance of fibre post-restored teeth with varying ferrule alignments. The fracture of the post-restored teeth was modelled using XFEM, which showed	In fracture failure tests, the palatal ferrule significantly increased the fracture resistance of root-treated teeth, regardless of labial ferrule height, and increasing palatal ferrule height reduced stress concentration.

Sr.no.	Authors	Study variables	Conclusion
		crack initiation and propagation inside the cement layers.	
13	Juloski et al	The effect of varied ferrule heights on stress distribution in root-treated maxillary first premolars was studied. Four models were developed with varying degrees of coronal tissue loss (0 mm, 1 mm, 2 mm, and 3 mm ferrule height). Within the root, post, abutment, crown, and related adhesive boundary, the principal stresses values and distribution were recorded.	Composite abutments in FE models in comparison to FE-models with ferrule, greater stress was detected when no ferrule was present. With increasing ferrule height, stress values at the adhesive boundaries decreased. Root-treated teeth with a higher ferrule show decreased stress at the abutment-root and post-abutment boundaries.
14	Aarti Rajambigai et al	Using 3D FEA, the researchers compared the stress dissipation within a maxillary central incisor with titanium and glass fibre posts, ferrules, and no ferrule. The stress distribution was determined at the post-cement-dentin border, which is more susceptible to fracture.	The results of the study revealed that it is desirable to integrate a ferrule of coronal dentin on every occasion posts are used. Fracture resistance can be upgraded by integrating a ferrule. A ferrule plays vital role in strengthening the residual tooth structure.

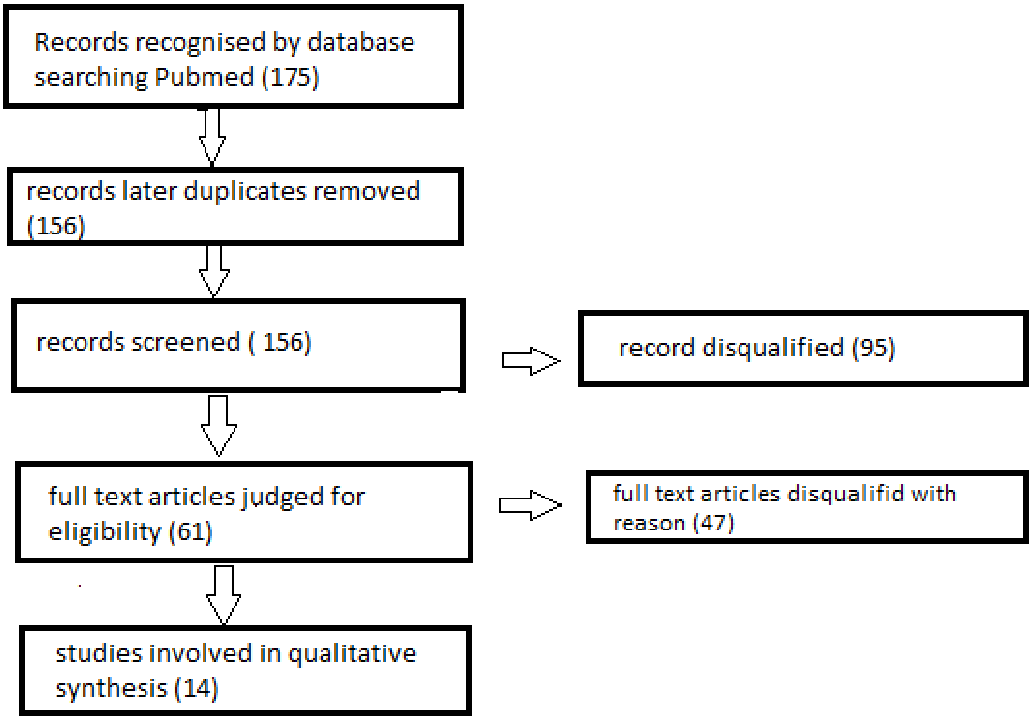

Fig. 1. Review flow chart (PRISMA 2009)

2.3 Data Extraction

Screening and revising of papers was conceded by a sole researcher. In case of unclear situation for inclusion criteria, a second investigator judged the full text and the verdict on inclusion of the article was fixed by conversation between the investigators. Finalized data confined information on type of tooth, location of tooth, magnitude of force, software used for modelling, boundary condition, method of scanning, validation, tooth with ferrule, tooth without ferrule, key findings.

3. RESULTS

14 papers were recognized for their contributions, which covered the following main topics: methodological aspects of modelling endodontically treated teeth with and without ferrules, and simulation-based intervention design to enhance stress distribution. We accomplished multi-database systematic review by PRISMA standards, short listed papers were assessed for methodological quality and results were scrutinized for eligible papers. The bulk of the papers demonstrated human tooth jaw assembly. Finite element models employed either patient-specific geometrical measurement or idealized average geometry. Assortments in choice of boundary conditions, material properties and loading condition were established in the finite-element models.

FE models can collect a large amount of detailed data and make analyzing it easier. Data was frequently presented visually as color-coded maps and simple magnitude-based variables like Von Mises stresses, surface pressures, or shear forces inside anatomical regions of interest in the short-listed publications [5-18]. Tables 1–2 list the primary output methods used by the studies under consideration.

4. DISCUSSION

This (FEA) system aids in the solution of a multifarious mechanical problem by dividing the problem domain into smaller components into which the field variables can be merged with the use of form functions [19]. Because of the versatility of the FEA method in computing stress dispersals inside complex structures, understanding of dental biomechanics has gotten easier as computer technology has advanced. The researcher will be more prepared to grasp the outcomes of FEA research and apply these findings to clinical situations if they adapt the basic theory, technique, constraints, and application of FEA. Future research should emphasize on analyzing stress dispersals in case of dynamic loading environments of mastication, which may improve to simulate the actual clinical condition [19].

4.1 Model Design

Based on the publications reviewed [5-18], it is obvious that CT and MRI scans are the two most commonly used imaging tools for this purpose, as they provide higher image quality and allow for more precise bone or soft tissue geometry restoration.

The first essential demand for clinically relevant FE modelling is the non-invasive and cost-effective collection of valid information for geometry plan/reconstruction. In circumstances when CT or MRI are already part of the patient's standard treatment, FEA modelling is more convenient. Realistic mathematical models of the full tooth and jaw assembly are commonly reconstructed from CT scans, which are more suited for imaging bones, or MRI scans, which are better suited for imaging soft tissues. In a few investigations, CT and MRI were combined to produce a more detailed reconstruction of both bone and soft tissues. Geometry reconstruction in this situation entails the segmentation of various hard and soft tissues into a sequence of images that mimic distinct sections of a tooth and its accompanying structure [5-8]. For 3D reconstruction of tissue geometry and manual segmentation, the majority of the examined research used specialized software (e.g., ANSYS, CATIA, etc.).

4.2 Meshing

Only a few articles [5-8,10,14], went into detail about the mesh density and the kind of elements used. Because of the complexity of the figures and the simulation of materials with non-linear mechanical behaviour, one of the main drawbacks of geometrically detailed models is their high computational costs.

4.3 Assignment of Material Properties

To simulate complex, non-linear mechanical behavior of all biological tissues is seems to be the most challenging part. Most of the reviewed papers [5-18] consigned material properties based on previous literature.

4.4 Loading

Identifying boundary conditions and loads for models that can allocate clinically relevant loading without the use of specialised equipment or time-consuming assessments is critical. According to the research, assessing past criterion measurements from literature or in vivo investigation appears to be the most prevalent technique to estimate loading [4].

4.5 Interpretation of Results

Unlike in-vitro single value failure load results, the results of a FEA on the restored system include information about the stress dispersal of each component of the restoration. Three conditions must be met in order to accurately interpret FEA data. First, the FEA must adequately represent real stress values; second, the strength of various materials must be recognized; and third, an appropriate failure criterion must be employed [20].

The majority of the researchers [5-18] modelled teeth and related structures as isotropic, rather than orthotropic. The finite element model represents a static scenario at the time of load presentation, rather than actual clinical conditions. Masticatory pressures are more dynamic and cyclic in real-life clinical situations. Homogeneous, isotropic, and elastic tooth and accompanying structures were assumed. If the material qualities are considered non-homogeneous and anisotropic, more precise measurements can be made, but this setup necessitates significantly more difficult mathematical calculations. As a result, a non-linear elastic-plastic material model is preferable to the linear models employed in most FEA analyses [21].

4.6 Validation

The most difficult part of integrating any FE modelling system into clinical practice is ensuring that it can generate credible models for any member of the population for whom it was designed [22]. This means that the accuracy of each component of the modelling process, as well as the entire process as a whole, will need to be evaluated in large cohort studies in order to determine its correctness for populations rather than simply individuals. These validation tests will not need to be implemented in the clinic as part of day-to-day practice, allowing for more intricate, thorough, but also time-consuming and costly procedures, such as the combined use of medical imaging [23,24]. A combination of in vivo mechanical testing and advanced computer analytic approaches is necessary to produce reliable results. The majority of the publications [5-8,10-14,18] that were examined did not do any kind of validation.

4.7 Ferrule Effect

There is mixed judgment regarding the effectiveness of ferrule in enhancing the threshold of failure load in root treated tooth. Some mechanical studies approve the assignment of ferrule as it consults increased resistance to fracture in pulp less tooth. The ferrule effect in post and core repaired teeth promotes durability, but also intensifies pressures in the dentin in teeth with no supragingival structure. (5) The adhesive borders are the most vulnerable sections of the FE models that have been evaluated, with debonding being the most common cause of failure. Separation at the post-abutment and abutment-root boundary is expected exclusively in teeth without ferrule, whereas lower stresses were predicted in FE-models with ferrule. Less tension at adhesive boundaries is seen in root-treated teeth with a larger ferrule, which can be expected to reduce the risk of clinical failure [3].

5. LIMITATIONS

In case of most of included studies, the accuracy is determined by the precision of the generated mathematical model of the tooth and accompanying structures. All materials are measured as homogeneous and have a linear response to stress, despite the fact that this is not the case in the real world. In clinical practice, the stress response to these structures is more complicated. Instead of true dynamic cycle loads focusing at the tooth surface during mastication, obliquely applied static loads will be predicted [6-10] The vast majority of the publications studied did not provide any form of validation.

6. CONCLUSION

Improvement in future modeling concluded by the results of this review may profit valuable insights into ideal treatment protocol of pulp less tooth. The stress-reduction effect of the ferrule effect in teeth with posts and cores is precarious [25,26,27]. Teeth are less stressed when strong materials are used for the post and core [28,29,30]. Because the survival of an endodontically treated tooth is dependent on the amount of sound tooth structure left after endodontic access and caries removal, the most important factors in restoring an endodontically treated tooth are the maximum preservation and conservation of enamel, dentin, and the dentinoenamel junction [31]. Keeping tooth structure above the gingiva enclosed by the crown gives repaired teeth the most strength [32]. Increased ferrule height leads to a reduction in von Mises stress in the post and post-dentin interface, with transfer of von Mises stress to the root cervical area from the mid-root and apex.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

CONSENT

It is not applicable.

ETHICAL APPROVAL

It is not applicable.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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