Review Article

Finite element analysis of biomechanical behaviour of remaining coronal dentin in endodontically restored tooth - a systematic review [evaluation of stress distribution in fea studies]

Abstract

Background:

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

Methods:

14 applicable paper 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 studies illustrated use of FE analysis for replication of incorporating nonlinear tooth and tissue mechanics, contact 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 method in dental biomechanics due to its flexibility in calculating stress dispersals within multidimensional structures. By learning the basic theory, method, application and restrictions of FEA in dentistry, the researcher will be well furnished to interpret results of FEA studies and correlate these results to clinical circumstances. Ferrule has a precarious impact on stress reduction. Using posts and

cores made of stiff materials leads to stress reduction in teeth. keeping supragingival tooth structure incorporated by crown provides the extreme strength to restored teeth .

Keywords: ferrule , post and core, finite element analysis

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 have 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.

This paper contains a systematic review and brief of the conclusions from FE analysis grounded computational simulations of the tooth with post and core to simulate function and tissue performance.

MATERIALS AND METHODS

We shortlisted original research papers that employed FE models of the tooth restored with post and core to replicate function, tissue behavior. 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. Full text papers were considered to conclude if they cover the inclusion standards.

Search Strategy

PubMed search was directed for papers issued in dental journals in English. Eligible studies were short listed using the collective terms: “FERRULE ,” “FINITE ELEMENT ANALYSIS”, “ STRESS DISTRIBUTION”

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).

INCLUSION CRTITERIA :

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

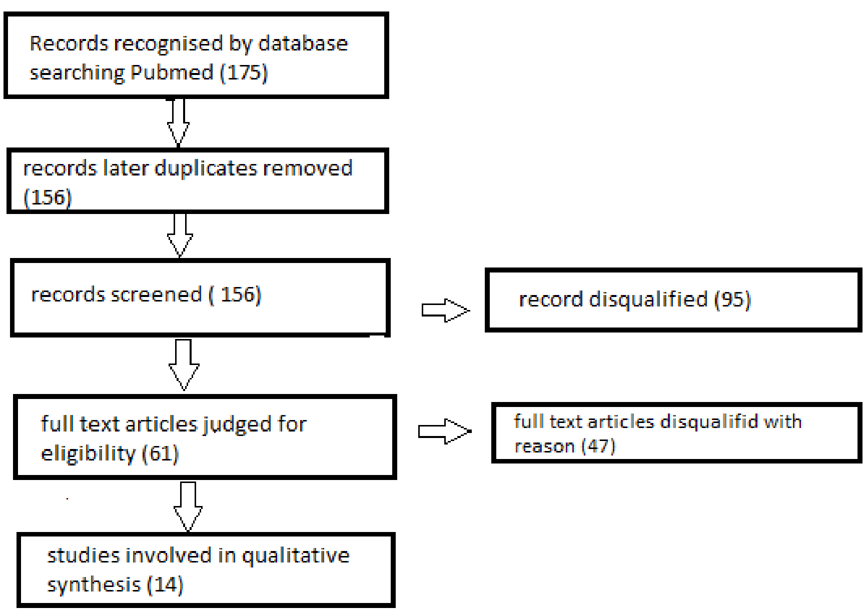

Fig 1. Review flow chart (PRISMA 2009)

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.

Table 1. Characteristics of the Included Studies

S r n o.	Ref	Year of publication	Country of publication	Study type	Method of scanning	Modelling software	Fea software	Type of tooth	Type of loading	Validation
1				3D	3D laser Dental Scanner D250 (3ShapeA/ S)				100 N cingulum,	No

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	Beata et al(5)	2013	Poland	FEA	a CT scan of the tooth XCB-500/I-CAT		ANSYS 14	maxillary first incisors	at 130◦ to the longitudinal axis	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	300-N the central lingual surface of the prosthesis 3.0 mm under the cusp and at 5 degrees angle	No validation
3	Mahmoudi et al (7)	2017	Iran	3D FEA	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
5	**Roscoe et al**(9)	2013	Uberlandia	3D FEA	DT3D database	Rhinoceros 3D, Seattle, Wa	NeiNASTRAN software; Norann Engineering Inc, Westminster, Calif	maxillary canine	load of 100 N 15-degree angle 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	No validation experiment

								r	surface 45 degree to its long axis	included in protocol
7	**F. R. 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 package (Siemens PLM Software Inc., Santa Ana, CA, USA). Refinement of model 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, Tx, USA	maxillary central incisor	Force of 100 N at an angle of 45° was applied 2 mm above to the incisal edge on the lingual surface.	No validation experiment included in protocol
9	***Ausiello et al*** (13)	2017	Italy	3D FEA	a micro-CT scanner system	ScanIP®3.2 module (Simpleware Ltd.) Bruker microCT, Kontich, Belgium Rhinoceros© 5.0	HyperWork®14.0 (Altair EngineeringInc.)	canine	50 N was applied at 45 degree to the long axis of the tooth, on the lingual surface	No validation
10	***Santos-Filho et al***(14)	2014	Brazil	3D FEA	scanning of tooth a maxillary central incisor. The *.STL	Computer Assisted Engineering, Femap 10.1; Velocity Series,	(NEiNastran 9.2; Noran	maxillary central incisor.	100 N load was applied at 135 degree	No validation

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					files created and were imported to CAD software	Siemens PLM Software, Plano, TX CAD Rhinoceros 3D 4.0; McNeel North America, Seattle, WA	Engineering, Westminster, CA),		angle, with long axis of tooth	
11	**Rodrigues et al**(15)	2017	Uberlandia	3D FEA	Scaning done by using interactive medical imaging software	3-Matic 8.0, Materialise Mimics 16.0; Materialise, Leuven, Belgium. MSC.Patran 2010(MSC Software, Santa Ana, CA)	MSC. Marc /MSC.Mentat	maxillary central incisor	155-N vertical force .	validation experiment included in protocol
12	**Zhang et al**(16)	2014	China	3D FEA	a laser-based 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, directed at 45◦to the longitudinal axis of the tooth	validation experiment included in protocol
14	**Rajambigai et**	2016	india	3D FEA	modeled with geometric	PRO Engineer	ANSYS	maxillary	100 N load with	No validation

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	al(18)				data	software (Parametric Technology Corporation, USA).	WORKBENCH 10.0software	central incisor	an angle of 45o to the long axis of the tooth.	experiment included in protocol

Table 2. – Clinical findings

Sr.no.	Authors	Study variables	Conclusion
1	Beata et al	Study evaluated the effect of ferrule and length of cast post and cores and FRC posts on the biomechanical integrity of anterior teeth. Study investigated the strength of tooth tissues, ceramics and composites, for FRC the Tsai-Wu criterion and for cast Ni Cr alloy the von Mises criterion carried out.	Effect of ferrule in teeth diminishes stresses in post,dentin and in luting cement. The tensile stresses around posts with ferrule effect were 1.7–3.0 times condensed than teeth with no ferrule. Cast posts restored teeth exhibited favorable stress dispersal in comparison with FRC posts. Posts and cores made of rigid materials leads to stress reduction in teeth.
2	Chen et al	Study measured the stress dispersal in the post-core system and root structure of a maxillary canine with different ferrule configuration. Von Mises stresses were evaluated by applying a 300 N load to the middle of the lingual surface of the prosthesis.	Increased ferrule height leads to reduced von Mises stress in the zirconia post and the post-dentin interface, Reduction in the maximum von Mises stress in mid and apical region of root when the ferrule height increased from 0 to 3 mm seen.
3	Mahmoudi et al	Study assessed whether an inhomogeneous post can reduce the hazardous stresses in the dentin and at the interfaces. A 3-D model of the post –core treated first premolar tooth was modeled with and without a ferrule.Stresses at the dentin-adhesive interface were measured to consider the threat of loss of adhesion.	Presence of the ferrule reduced the stresses at interface. Without a ferrule, the stresses at the post cement were more than the stresses at the crown cement in all models except the carbon fiber post.
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	The results of study discovered that maxillary premolars with facial dentin enduring show advanced local stress on root portion of dentin. Changing the loading position and dropping the facial cusp inclination can diminish local

		Mises stress.	stresses.
5	Roscoe et al	A researcher evaluated the outcome of alveolar bone loss, post type and ferrule presence on the biomechanical behavior of endodontically treated maxillary canines. Research was conceded with a combination strain measurement and finite element analysis, for understanding of the failure criteria. The models were analyzed by by means of the maximum principal stress criteria for stress dispersal.	Results of study revealed that the existence of a ferrule enhanced the mechanical behavior. The nonappearance of a ferrule meaningfully increased the buccal and proximal strain values.
6	Watanabe et al	Researcher investigated the impact of ferrule height (0, 1, and 2 mm) on the tooth structure. The equivalent von Mises stress, maximum principal stress, minimum principal stress and shear stress were calculated within different parts of tooth structure using the FE software.	It was observed that the rise in ferrule size condensed the maximum principal stress, concentration in all structures of models. Teeth with no ferrule are more inclined to the occurrence of fractures in the apical root third.
7	F. R. Verri et al.	Researcher evaluated the biomechanical behaviour of a tooth rehabilitated with metal-free crowns installed in teeth with no coronal structure, while varying the posts used. Maximum principal stress was used for calculation of non-ductile constituents with superior possibility of fracture	Glass fiber posts in teeth with no remaining tooth structure results in inferior stress along the post, but greater stress in the simulated tooth region, which could threaten restoration stability.
8	Upadhyaya , et al	Study investigated the influence of design and material of post with or no ferrule on stress dispersal using finite element analysis.12 3D models of post retained central incisors with and without ferrule, different post material were completed. Results were investigated using 3D von Mises criteria.	The study outcome revealed that ferrule provides uniform dissemination of stresses and decreases the cervical stresses.
9	Ausiello et al	Study assessed the effect of a ferrule design with specific post material shape combinations on the mechanical behavior of post-restored canine teeth.Four models were analysed by Finite Element (FE) Analysis: with/without a ferrule for both types of post material and shape.The maximum normal stress criterion was adopted as a measure of potential damage.	Researcher concluded that models without a ferrule showed greater stresses (16.3 MPa) than those for modelswith a ferrule (9.2 MPa). With a ferrule, stress was uniformly dispersed along the abutment and the root, with no precarious stress concentration.
10	Santos-Filho et al.	Study evaluated the influence of post system, length, and ferrule on biomechanical behavior of root treated anterior teeth . Results were assessed by von Mises criterion.	The presence of ferrule increases the fracture resistance for endodontically treated teeth regardless of the post system Ferrule was a determining factor in the strain, fracture resistance and fracture pattern.
	Rodrigues et al.	Study was carried out to trial the effect of ferrule designs on both maxillary central incisors refurbished with glass fiber posts and all-ceramic restorations (CAD-CAM)by means of 3D FEA.	The stress analysis study established significance of preserving the coronal structure in root treated teeth and that growing

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11		Strain gauges used to measure ceramic strain during bite force recording for FEA validation. Modified von Mises equivalent stress was considered for stress evaluation.	the ferrule height along the entire root circumference recovers the stress dispersal. The absence of a ferrule in the proximal region caused in greater stress concentrations in root dentin and also in the root canal.
12	Zhang et al	Study evaluated the fracture resistance of fibre post-restored teeth with various ferrule alignments by using extended finite element analysis (XFEM)and fracture failure tests .XFEM was used to model the fracture of the post-restored teeth and exhibit crack initiation and propagation within the cement layers	Fracture failure tests indicated that the palatal ferrule considerably boosted the fracture resistance of the root treated teeth, irrespective the height of the labial ferrule and Increasing palatal ferrule height reduce the stress concentration.
13	Juloski et al	Researcher investigated the influence of different ferrule heights on stress dispersal within root treated maxillary first premolar. Four models with different degrees of coronal tissue loss (0 mm, 1 mm, 2 mm and 3 mm of ferrule height) were created. Principal stresses values and distribution were recorded within root, post,abutment, crown and related adhesive border.	FE models with composite abutments higher stress was observed when no ferrule was present compared to FE-models with ferrule. Stress values at the adhesive borders declined with increasing ferrule height. Root treated teeth with higher ferrule display lesser stress at post-abutment, abutment-root borders.
14	Aarti Rajambigai et al	Study was aimed to compare the stress dispersal within a maxillary central incisor with titanium and glass fiber posts, with and no ferrule using 3D FEA The stress distribution was calculated at the post-cement-dentin border which is more prone 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.

Results :

14 relevant papers were acknowledged covering main primary subjects: methodological aspects relevant to modelling the endodontically treated tooth with and without ferrule design and simulation based design of interventions to improve 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 gather a enormous amount of detailed evidence and simplifies interpreting these data. In the short listed articles, data was regularly provided visually as color coded maps and simple magnitude-based variables like Von Mises stresses, surface pressures or shear forces within anatomical regions of interest. Primary output methods utilized by the reviewed studies are enumerated in Tables 1–3.

Discussion

This (FEA) system plays important role in finding a solution to a multifaceted mechanical problem by distributing the problem domain into simpler elements where the field variables can be merged by using shape functions. With advances in computer technology, understanding of dental biomechanics becomes easier because of resourcefulness of FEA method in calculating stress dispersals within complex structures. By adapting the basic theory, method, restrictions and application of FEA, the researcher will be better prepared to understand results of FEA research and conclude these results to clinical circumstances. Future research should emphasize on ~~analysing~~analyzing stress dispersals in case of dynamic loading environments of mastication, which may improve to simulate the actual clinical condition.(19)

Model design

Based on the reviewed papers (references), it is clear that CT and MRI scan are the two most frequently used imaging tool for this purpose, as it deals greater image quality permitting the accurate refurbishment of bone or soft tissue geometry.

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The first key demand towards clinically relevant FE modelling is assembling reliable information for geometry plan/ reconstruction in a non-invasive and cost effective and way(references). It is more convenient to do FEA modelling in cases where CT or MRI are already included into the patient's standard treatment(references).

Realistic mathematical models of the entire tooth and jaw assembly are usually reconstructed either from CT, which is more suited for imaging bones and MRI scan for soft tissues. CT and MRI were also combined in few studies (references) to yield a more detailed reconstruction of both bone and soft tissues. In this case, geometry reconstruction contains the segmentation of different hard and soft tissues in a series of images that resembles to different sections of tooth and associated structure. Most of the reviewed studies (references) hired specialized software (e.g. ANSYS, CATIA etc.) for 3D reconstruction of tissue geometry and the manual segmentation.

Meshing:

Very few papers (references)presented details about density of mesh and type of elements that was used. Due to complex figures, simulation of material exhibiting non-linear mechanical behavior, it becomes obvious that one of the main shortcomings of geometrically detailed models is their high computational costs(references).

Assignment of material properties

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

Loading

It is very imperative to identify boundary conditions and loading for the models which will able to allocate clinically relevant loading without the need for specific equipment and timeconsuming measurements(references). According to literature(references), the common way to estimate loading seems to be assessing previous criterion measurements from literature or in vivo investigation.

Interpretation of results

The results achieved from a FEA on the restored system enclose facts about the stress dispersal of each component of the restoration, unlike in-vitro single value of failure load result. To obtain accurate interpretation of FEA results, three conditions must be fulfilled. First, FEA should sufficiently represent the real stress values; second, strength of the different materials must be acknowledged; third, an suitable failure criterion must be used.(20)

Most of the researchers modeled tooth and associated structures as isotropic and not orthotropic. The finite element model signifies a static situation at the moment of load presentation and not a real clinical circumstances. In actual clinical condition, masticatory forces are more dynamic and cyclic. Tooth and associated structures were presumed to be homogenous, isotropic and elastic. More particular measurements can be achieved if the material properties are considered as non-homogeneous and anisotropic, but such setup involves much more difficult mathematical calculations. Therefore, a non-linear elastic-plastic material model is considered better than the linear models that are used in most FEA studies.(21)

Validation

The eventual condition for the execution of any FE modelling system into clinical practice is to ensure that whether it can produce dependable structural models for any person in the population for which it was established.(22) To achieve accurate results a amalgamation of in vivo mechanical testing and advanced computational analysis techniques is required. It is observed that most of the reviewed papers did not carry out any kind of validation.

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 pulpless tooth. Post and core restored teeth with ferrule effect increases durability, but intensifies stresses in dentin in teeth wih no supragingival structure.(5) The adhesive boundaries are the fragile parts of the tested FE models and debonding is the most common cause of failure. At the post-abutment and the abutment-root border separation is anticipated to occur only in teeth with no ferrule, whereas lesser stresses were estimated in FE-models exhibiting ferrule. Root treated teeth having greater ferrule reveal lesser stresses at adhesive boundaries which may be anticipated to minmise the possibility of clinical failure. (3)

Clinical Implications

Improvement in future modeling concluded by the results of this review may profit valuable insights into ideal treatment protocol of pulpless tooth. Effect of ferrule effect in teeth with posts and cores has a precarious impact on stress reduction(references). Using stiff materials for post and core leads to stress reduction in teeth. Keeping tooth structure above gingiva embraced by crown offers the greatest strength to restored teeth(references). Reduction in von Mises stress in the post and the post-dentin interface seen in increased ferrule height, with deceptive shift of von Mises stress to the root cervical area from the mid-root and the apex(references).

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. 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.*

References

1. Fernandes AS, Dessai GS. Factors Affecting the Fracture Resistance of Post-Core Reconstructed Teeth: A Review. 2001;10. PMID: 11508092

2. Sorensen JA, Engelman MJ. Ferrule design and fracture resistance of endodontically treated teeth. J Prosthet Dent. 1990 May;63(5):529–36. doi: 10.1016/0022-3913(90)90070-s.

3. Juloski J, Apicella D, Ferrari M. The effect of ferrule height on stress distribution within a tooth restored with fibre posts and ceramic crown: A finite element analysis. Dent Mater. 2014 Dec;30(12):1304–15. doi: 10.1016/j.dental.2014.09.004. Epub 2014 Oct 8.

4. Murakami N, Wakabayashi N. Finite element contact analysis as a critical technique in dental biomechanics: A review. J Prosthodont Res. 2014 Apr;58(2):92–101. doi: 10.1016/j.jpor.2014.03.001.

5. Dejak B, Młotkowski A. The influence of ferrule effect and length of cast and FRC posts on the stresses in anterior teeth. Dent Mater. 2013 Sep;29(9):e227–37. doi: 10.1016/j.dental.2013.06.002.

6. Chen D, Wang N, Gao Y, Shao L, Deng B. A 3-dimensional finite element analysis of the restoration of the maxillary canine with a complex zirconia post system. J Prosthet Dent. 2014 Dec;112(6):1406–15. doi: 10.1016/j.prosdent.2014.05.017. Epub 2014 Jul 1.

7. Mahmoudi M, Saidi AR, Amini P, Hashemipour MA. Influence of inhomogeneous dental posts on stress distribution in tooth root and interfaces: Three-dimensional finite element analysis. J Prosthet Dent. 2017 Dec;118(6):742–51. http://dx.doi.org/10.4103/1735-3327.310039

8. Liu S, Liu Y, Xu J, Rong Q, Pan S. Influence of occlusal contact and cusp inclination on the biomechanical character of a maxillary premolar: A finite element analysis. J Prosthet Dent. 2014 Nov;112(5):1238–45. doi: 10.1016/j.prosdent.2014.04.011. Epub 2014 May 16.

9. Roscoe MG, Noritomi PY, Novais VR, Soares CJ. Influence of alveolar bone loss, post type, and ferrule presence on the biomechanical behavior of endodontically treated maxillary canines: Strain measurement and stress distribution. J Prosthet Dent. 2013 Aug;110(2):116–26. doi: 10.1016/S0022-3913(13)60350-9.

10. Watanabe MU, Anchieta RB, Rocha EP, Kina S, Almeida EO de, Junior ACF, et al. Influence of Crown Ferrule Heights and Dowel Material Selection on the Mechanical Behavior of Root-Filled Teeth: A Finite Element Analysis: Crown Ferrule Height and Dowel Material Selection. J Prosthodont. 2012 Jun;21(4):304–11. DOI: 10.4103/sej.sej_292_20

11. Verri FR, Okumura MHT, Lemos CAA, Almeida DA de F, de Souza Batista VE, Cruz RS, et al. Three-dimensional finite element analysis of glass fiber and cast metal posts with different alloys for reconstruction of teeth without ferrule. J Med Eng Technol. 2017 Nov 17;41(8):644–51. doi: 10.1080/03091902.2017.1385655.

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12. Upadhyaya V, Bhargava A, Parkash H, Chittaranjan B, Kumar V. A finite element study of teeth restored with post and core: Effect of design, material, and ferrule. Dent Res J. 2016;13(3):233. doi: 10.4103/1735-3327.182182.

13. Ausiello P, Gloria A, Maietta S, Watts DC, Martorelli M. Stress Distributions for Hybrid Composite Endodontic Post Designs with and without a Ferrule: FEA Study. Polymers. 2020 Aug 16;12(8):1836. doi: 10.3390/polym12081836

14. Santos-Filho PCF, Veríssimo C, Soares PV, Saltarelo RC, Soares CJ, Marcondes Martins LR. Influence of Ferrule, Post System, and Length on Biomechanical Behavior of Endodontically Treated Anterior Teeth. J Endod. 2014 Jan;40(1):119–23. doi: 10.1016/j.joen.2013.09.034. Epub 2013 Oct 27.

15. Rodrigues M de P, Soares PBF, Valdivia ADCM, Pessoa RS, Veríssimo C, Versluis A, et al. Patient-specific Finite Element Analysis of Fiber Post and Ferrule Design. J Endod. 2017 Sep;43(9):1539–44. doi: 10.1016/j.joen.2017.04.024. Epub 2017 Jul 20.

16. Zhang YY, Peng MD, Wang YN, Li Q. The effects of ferrule configuration on the anti-fracture ability of fiber post-restored teeth. J Dent. 2015 Jan;43(1):117–25. DOI: 10.1016/j.jdent.2014.10.003

17. Juloski J, Radovic I, Goracci C, Vulicevic ZR, Ferrari M. Ferrule effect: a literature review. J Endod. 2012 Jan;38(1):11–9. doi: 10.1016/j.joen.2011.09.024. Epub 2011 Nov 13.

18. Rajambigai A. Comparison of Stress Distribution in a Maxillary Central Incisor Restored with Two Prefabricated Post Systems with and without Ferrule Using Finite Element Method. J Clin Diagn Res [Internet]. 2016 [cited 2021 Jul 23]; Available from: http://jcdr.net/article_fulltext.asp?issn=0973-709x&year=2016&volume=10&issue=9&page=ZC52&issn=0973-709x&id=8492

19. Geng J-P, Tan KBC, Liu G-R. Application of finite element analysis in implant dentistry: A review of the literature. J Prosthet Dent. 2001 Jun;85(6):585–98. doi: 10.1067/mpr.2001.115251.

20. Pérez-González A, Iserte-Vilar JL, González-Lluch C. Interpreting finite element results for brittle materials in endodontic restorations. Biomed Eng OnLine. 2011;10(1):44. DOI:10.1186/1475-925X-10-44

21. Jongsma LA, Ir. N de J, Kleverlaan CJ, Feilzer AJ. Reduced contraction stress formation obtained by a two-step cementation procedure for fiber posts. Dent Mater. 2011 Jul;27(7):670–6. doi: 10.1016/j.dental.2011.03.008. Epub 2011 Apr 22.

22. Chang Y, Tambe AA, Maeda Y, Wada M, Gonda T. Finite element analysis of dental implants with validation: to what extent can we expect the model to predict biological phenomena? A literature review and proposal for classification of a validation process. Int J Implant Dent. 2018 Dec;4(1):7. doi: 10.1186/s40729-018-0119-5.

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