Research Article

Critical evaluation of fracture strength testing for endodontically treated teeth: a finite element analysis study

Emel Uzunoglu-Özyürek,¹ Selen Küçükkaya Eren,¹ Oğuz Eraslan,² Sema Belli²

¹Department of Endodontics, Faculty of Dentistry, Hacettepe University, Ankara, Turkey
²Department of Prosthodontics, Faculty of Dentistry, Selcuk University, Konya, Turkey

ABSTRACT

Objectives: The aim of this study was to investigate whether the diameter and direction of the plunger and simulation of the periodontal ligament (PDL) affected the stress distribution in endodontically treated premolars.

Methods: A fracture strength test was simulated via finite element analysis. A base model was set up, and the following parameters were modified: plunger diameter (3 mm vs. 6 mm), plunger direction (vertical vs. 135° angular to the central fossa), and PDL simulation. The analysis was conducted using the CosmosWorks structural analysis program, and the results are presented in terms of von Mises stresses.

Results: The smaller plunger increased the stresses at the contact area of the crown, but the plunger diameter had no effect on the stress distribution within the root. An angular plunger direction increased stresses within the root, as well as at the buccal cusp of the crown, compared with the vertical direction. Simulation of the PDL caused higher stress accumulation, especially in the cervical region of the root.

Conclusions: The plunger diameter had no effect on the stress distribution in the roots, whereas the plunger direction and PDL simulation did affect the stress distribution. More stringent standards can be established by taking such parameters into account when performing fracture testing in future studies.

Keywords: Endodontics; Finite element analysis; Fracture strength; Periodontal ligament

INTRODUCTION

The major goals of root canal treatment are to treat the infection and to preserve the health and functionality of the tooth. Although the survival rate of initial root canal treatment is higher than 90% [1,2], endodontically treated teeth can be extracted for various reasons, such as non-restorable caries, periodontal disease, procedural errors during endodontic treatment, prosthetic reasons, and vertical root fractures (VRFs) [3,4]. VRFs are one of the most common reasons for extraction of an endodontically treated tooth [3]. The prevalence of VRFs was reported to be 11%–20% in extracted endodontically treated teeth [4]. Excessive
loss of tooth structure is associated with an increased risk of VRF, which often results from caries or trauma, access cavity preparation, and root canal instrumentation [5,6].

To date, many studies have evaluated the effects of various treatment protocols and applications, including root canal obturation with different filling materials and the application of different post-endodontic restorations, on the fracture strength of endodontically treated teeth [7,8]. However, divergent conclusions have been reported regarding the effect of such procedures on the fracture strength of endodontically treated teeth, potentially due to methodological differences among the studies. The applied parameters of in vitro fracture tests, such as the diameter and direction of the plunger and simulation of the periodontal ligament (PDL), vary among studies. Although in vitro studies provide a platform to create, compare, and check materials or techniques prior to their clinical application, the majority of them lack consistency. According to recent reviews, standardization of in vitro studies would promote quality and transparency in the reported results [9,10].

Finite element analysis (FEA) is an engineering method that is used to determine the stress distribution when a force is applied to a structure by the numerical analysis of complex structures based on their material properties. In this framework, the von Mises stress criterion is generally used to interpret the results. von Mises stress is a measure that accounts for various stress components, including tensile, compressive, and shear stresses, alone or in combination. von Mises stresses depend on the entire stress field and are widely used as an indicator of the possibility that damage will occur [11]. Furthermore, the factors that affect fracture susceptibility can be determined using FEA [12,13]. Therefore, the aim of this study was to use FEA to evaluate the effects of variation in the test parameters used in fracture strength analysis, such as the diameter and direction of the plunger and simulation of the PDL, on the stress distribution in an endodontically treated mandibular premolar. The null hypothesis of this study was that applying different test parameters during fracture strength analysis would not affect the stress patterns or concentrations.

MATERIALS AND METHODS

Three-dimensional (3D) FEA was conducted using the SolidWorks 2007 9.0.3 structural analysis program (SolidWorks Corp., Waltham, MA, USA), as in a previous study [14]. Briefly, the CosmosWorks Program (SolidWorks Corp.) was used to perform linear elastic FEA. The sequentially performed procedures are shown in Figure 1. A 3D FEA mathematical model simulating a mandibular premolar tooth with supporting tissues was created. The average anatomic dimensions of the alveolar bone and PDL were generated according to data in the literature [15]. The geometry used for the tooth model was described previously [16]. Accordingly, a model of a tooth obturated with gutta-percha was created. Composite resin fillings were then added to this model. The geometric models were meshed with tetrahedral quadratic elements, and each model consisted of approximately 275,000 nodes and 180,000 tetrahedral solid elements. The exterior nodes of the models’ bone structures were fixed in all directions as the boundary condition. The materials used in the study were assumed to be homogenous and isotropic. The properties of the structures and materials are summarized in Table 1 [17-21]. Acrylic resin and elastomeric material (data provided from the SolidWorks Material Library) were used to simulate the alveolar bone and PDL, respectively, in order to represent in vitro test conditions. Access cavities in the models were assumed to be filled.
using composite resin. Eight finite element models were created in the present study (Table 2). To calculate the stress distribution, a 300-N static load was applied vertically or at a 135° angle to the central fossa. The results are presented in terms of von Mises stresses. To better visualize mechanical phenomena in the models, calculated numeric data were transformed into color graphics. Sections obtained from the 3D models were used to present the stress distribution, and the color scale was limited to between 0 and 0.5+ MPa.

RESULTS

Table 2 summarizes the maximum von Mises stress values (MPa). Figures 2 and 3 show the stress distributions that occurred within the test models. The diameter of the plunger affected the stress distribution within the crown, but it had no effect on the stress distribution within the root. The smaller plunger increased stresses at the contact area of the crown (Figures 2A, 2B, 3A, and 3B). The direction of the plunger affected the stress distribution in both the crown and root regions. When the plunger was directed angularly, higher stresses occurred at the buccal cusp of the crown and within the root (Figures 2B, 2D, 3B, and 3D). However, when the direction of the plunger was vertical to the long axis of the tooth, stress accumulation was localized at the center of the crown, and no significant stress accumulation was observed within the root (Figures 2A, 2C, 3A, and 3C). The simulation of the PDL affected the stress accumulation

| Model                        | Plunger diameter (mm) | Plunger direction | Vertical | Angular |
|------------------------------|-----------------------|-------------------|----------|---------|
| Periodontal ligament simulation (+) | 3                     | 1.445             | 1.189    |
|                              | 6                     | 1.091             | 1.318    |
| Periodontal ligament simulation (−) | 3                     | 1.445             | 1.189    |
|                              | 6                     | 1.084             | 1.318    |

*Data provided from the SolidWorks Material Library.
distribution within the root and caused higher stress accumulation in the cervical region of the root when an angular force was applied (Figure 2).

DISCUSSION

The effects of several parameters of fracture strength test on stress distribution in endodontically treated teeth were evaluated in the present study. FEA was chosen as a methodology, because it would be difficult to test the present hypothesis using an in vitro fracture strength test due to the difficulties in standardizing the age, dimensions, mineral content, and root canal anatomy of extracted teeth. Root fractures generally occur in areas of high stress concentration when a load is applied to the teeth during mastication [22]. FEA provides a qualitative and comparative methodology for evaluating stress distribution and accumulation in tooth structures, and enables many factors to be kept uniform during the analysis, unlike in vitro tests [23]. According to previous studies, FEA models correlated very well with the observed fracture pattern in fracture strength tests, demonstrating reliable predictability for VRF [23,24]. In the present study, a mandibular premolar tooth model was
used, as mandibular premolars have been reported to be susceptible to fracture [25] and have been commonly used for fracture strength analysis in previous studies [7,8].

The effect of PDL simulation during the fracture strength test was evaluated, in light of the discordant findings reported in previous studies. Soares et al. [26] reported that the root embedment method and PDL simulation had significant effects on the fracture resistance values of extracted teeth. In contrast, Marchionatti et al. [27] reported that simulation of the PDL did not affect fracture resistance. The divergent findings in previous research might be related to the inherent limitations of fracture strength testing, such as the use of extracted teeth. In the present study, the distribution and accumulation of stresses were affected by PDL simulation. Interestingly, simulation of the PDL caused increased stress accumulation, especially in the cervical region of the root, which has been reported to be one of the most vulnerable areas for the propagation of VRFs [28]. According to González-Lluch et al. [29], more accurate results could be obtained by simulating the PDL.

The diameter of the plunger is another parameter with inconsistent results in in vitro fracture strength studies [7,8]. In the present FEA results, the maximum stress concentrations exhibited changes at the contact area of the crown, but did not change within the root, when different
plungers were used. Therefore, the diameter of the plunger does not seem to be a distinctive factor when evaluating the fracture strength of roots in in vitro studies. In contrast, the direction of the plunger affected the distribution and accumulation of stresses in both the crown and root regions, similar to a previous study [30]. An angular direction resulted in increased stresses within the root, while a vertical direction caused no significant stress accumulation within the root. Considering the direction of mastication forces, applying an angular direction during a fracture strength test may represent the clinical situation more realistically.

Although FEA is a useful and multifunctional technique, it has some limitations. The precise and accurate simulation of the structure of teeth remains a challenge for FEA. Furthermore, in the most FEA experiments, it is assumed that the distribution of forces on the canal surface is uniform. However, this seldom occurs clinically [11]. Belli et al. [14] and Eraslan et al. [31] used the elastic properties of cortical/cancellous bone and PDL in their FEA studies. Belli et al. [14] reported that the maximum von Mises stress value observed in a composite resin–restored, root canal–treated model was 25.90 MPa, while Eraslan et al. [31] reported this value as 21.20 MPa. These values are higher than those obtained in the present study. Using the elastic properties of acrylic resin and elastomeric material in the current model could be another limitation of this study, as those materials do not exactly simulate clinical circumstances. However, the aim of this study was to explore the effects of variation in several parameters on the results of in vitro fracture strength studies. Therefore, the elastic values of acrylic resin and elastomeric material were preferred to ensure similarity to previous FEA studies [29,32]. In this regard, the present findings may be useful for comparison with the results of previous in vitro fracture resistance studies.

**CONCLUSIONS**

Within the limitations of the present study, the null hypothesis was rejected, and it can be concluded that the direction of the plunger and simulation of the PDL during fracture strength testing affected the distribution and accumulation of stresses within the root. Simulation of the PDL and applying angular forces instead of vertical forces can be recommended for future studies, considering the conditions of the intraoral environment. Standardization of these parameters would allow a more reliable comparison of the results obtained from various in vitro studies.

**REFERENCES**

1. de Chevigny C, Dao TT, Basrani BR, Marquis V, Farzaneh M, Abitbol S, Friedman S. Treatment outcome in endodontics: the Toronto study--phase 4: initial treatment. J Endod 2008;34:258-263. [PUBMED | CROSSREF](https://doi.org/10.5395/rde.2019.44.e15)

2. Fonzar F, Fonzar A, Buttolo P, Worthington HV, Esposito M. The prognosis of root canal therapy: a 10-year retrospective cohort study on 411 patients with 1175 endodontically treated teeth. Eur J Oral Implantology 2009;2:201-208. [PUBMED](https://doi.org/10.5395/rde.2019.44.e15)

3. Touré B, Faye B, Kane AW, Lo CM, Niang B, Boucher Y. Analysis of reasons for extraction of endodontically treated teeth: a prospective study. J Endod 2011;37:1512-1515. [PUBMED | CROSSREF](https://doi.org/10.5395/rde.2019.44.e15)

4. Tsesis I, Rosen E, Tamse A, Taschieri S, Kfir A. Diagnosis of vertical root fractures in endodontically treated teeth based on clinical and radiographic indices: a systematic review. J Endod 2010;36:1455-1458. [PUBMED | CROSSREF](https://doi.org/10.5395/rde.2019.44.e15)
5. Khasnis SA, Kidiyoor KH, Patil AB, Kenganal SB. Vertical root fractures and their management. J Conserv Dent 2014;17:103-110.

6. Zadik Y, Sandler V, Bechor R, Salehrabi R. Analysis of factors related to extraction of endodontically treated teeth. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2008;106:e31-e35.

7. Guneser MB, Akman M, Kolcu IB, Eldeniz AU. Fracture resistance of roots obturated with a novel calcium silicate-based endodontic sealer (BioRoot RCS). J Adhes Sci Technol 2016;30:2420-2428.

8. Hshad ME, Dalkılıç EE, Ozturk GC, Dogruer I, Koray F. Influence of different restoration techniques on fracture resistance of root-filled teeth: in vitro investigation. Oper Dent 2018;43:162-169.

9. Faggion CM Jr. Guidelines for reporting pre-clinical in vitro studies on dental materials. J Evid Based Dent Pract 2012;12:182-189.

10. Kritthikadatta J, Gopikrishna V, Datta M. CRIS Guidelines (Checklist for Reporting In-vitro Studies): a concept note on the need for standardized guidelines for improving quality and transparency in reporting in-vitro studies in experimental dental research. J Conserv Dent 2014;17:301-304.

11. Pegoretti A, Fambri L, Zappini G, Bianchetti M. Finite element analysis of a glass fibre reinforced composite endodontic post. Biomaterials 2002;23:2667-2682.

12. Hu T, Cheng R, Shao M, Yang H, Zhang R, Gao Q, Guo L. Application of finite element analysis in root canal therapy. In: Moratal D, editor. Finite element analysis. London: IntechOpen; 2010. p99-120.

13. Williams KR, Edmundson JT. A finite element stress analysis of an endodontically restored tooth. Eng Med 1984;13:167-173.

14. Belli S, Eraslan O, Eski ti aç i oğlu G. Effect of root filling on stress distribution in premolars with endodontic-periodontal lesion: a finite elemental analysis study. J Endod 2016;42:150-155.

15. Baumgaertel S. Cortical bone thickness and bone depth of the posterior palatal alveolar process for mini-implant insertion in adults. Am J Orthod Dentofacial Orthop 2011;140:806-811.

16. Ash MM, Nelson S. Wheeler’s dental anatomy, physiology, and occlusion. St. Louis, MO: Saunders; 2003.

17. Ausiello P, Apicella A, Davidson CL. Effect of adhesive layer properties on stress distribution in composite restorations—a 3D finite element analysis. Dent Mater 2002;18:295-303.

18. Craig RG, Peyton FA. Elastic and mechanical properties of human dentin. J Dent Res 1958;37:710-718.

19. Kawasaki T, Takayama Y, Yamada T, Notani K. Relationship between the stress distribution and the shape of the alveolar residual ridge—three-dimensional behaviour of a lower complete denture. J Oral Rehabil 2001;28:950-957.

20. Rees J, Jacobsen P. The elastic moduli of enamel and dentine. Clin Mater 1993;14:35-39.

21. Ruse ND. Propagation of erroneous data for the modulus of elasticity of periodontal ligament and gutta percha in FEM/FEA papers: a story of broken links. Dent Mater 2008;24:1717-1719.

22. Onnikin PA, Davis RD, Wayman BE. An in vitro comparison of incomplete root fractures associated with three obturation techniques. J Endod 1994;20:32-37.

23. Lertchirakarn V, Palamara JE, Messer HH. Finite element analysis and strain-gauge studies of vertical root fracture. J Endod 2003;29:529-534.

24. Sathorn C, Palamara JE, Messer HH. A comparison of the effects of two canal preparation techniques on root fracture susceptibility and fracture pattern. J Endod 2005;31:283-287.
25. Testori T, Badino M, Castagnola M. Vertical root fractures in endodontically treated teeth: a clinical survey of 36 cases. J Endod 1993;19:87-91.

PUBMED | CROSSREF

26. Soares CJ, Pizi EC, Fonseca RB, Martins LR. Influence of root embedment material and periodontal ligament simulation on fracture resistance tests. Braz Oral Res 2005;19:114-16.

PUBMED | CROSSREF

27. Marchionatti AM, Wandscher VF, Broch J, Bergoli CD, Maier J, Valandro LF, Kaizer OB. Influence of periodontal ligament simulation on bond strength and fracture resistance of roots restored with fiber posts. J Appl Oral Sci 2014;22:450-458.

PUBMED | CROSSREF

28. von Arx T, Bosshardt D. Vertical root fractures of endodontically treated posterior teeth: a histologic analysis with clinical and radiographic correlates. Swiss Dent J 2017;127:14-23.

PUBMED

29. González-Lluch C, Rodríguez-Cervantes P, Forner L, Barjau A. Inclusion of the periodontal ligament in studies on the biomechanical behavior of fiber post-retained restorations: an in vitro study and three-dimensional finite element analysis. Proc Inst Mech Eng H 2016;230:230-238.

PUBMED | CROSSREF

30. Yang HS, Lang LA, Molina A, Felton DA. The effects of dowel design and load direction on dowel-and-core restorations. J Prosthet Dent 2001;85:558-567.

PUBMED | CROSSREF

31. Eraslan Ö, Eraslan O, Eskitaçcioğlu G, Belli S. Conservative restoration of severely damaged endodontically treated premolar teeth: a FEM study. Clin Oral Investig 2011;15:403-408.

PUBMED | CROSSREF

32. Soares PV, Santos-Filho PC, Queiroz EC, Araújo TC, Campos RE, Araújo CA, Soares CJ. Fracture resistance and stress distribution in endodontically treated maxillary premolars restored with composite resin. J Prosthodont 2008;17:114-119.

PUBMED | CROSSREF