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RESEARCH AND EDUCATION

Influence of substance loss and restoration materials on the fracture resistance of 1-piece endodontic crowns: An in vitro study

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ABSTRACT

Statement of problem. How different restorative materials designed for computer-aided design and computer-aided manufacturing (CAD-CAM) and substance loss affect the fracture resistance of endodontically treated maxillary first premolars restored with 1-piece endodontic crowns is unclear.

Purpose. The purpose of this in vitro study was to assess the impact of various CAD-CAM restorative materials and residual tooth structure on the fracture resistance of endodontically treated maxillary first premolars restored with 1-piece endodontic crowns.

Material and methods. Sixty-four maxillary first premolars were endodontically treated and divided into 4 main groups (n=16) according to the restorative material: ZP: Zirconia 1-piece endodontic crowns group (IPS e.max ZirCAD Prime; Ivoclar AG); RM: Resin-modified 1-piece endodontic ceramic crowns group (Katana Avencia; Kuraray Noritake Dental Inc); LD: Lithium disilicate 1-piece endodontic crowns group (IPS e.max CAD; Ivoclar AG); and CG: A control group restored with zirconia posts, composite resin cores, and lithium disilicate crowns (IPS e.max CAD; Ivoclar AG). Teeth in subgroups had either 1 or 2 residual coronal walls (n=8). All specimens underwent dynamic loading for 1 200 000 loading cycles in a masticatory simulator. A universal testing machine was then used to quasi-statically load the specimens at 30 degrees until fracture. For the statistical test, the Generalized Linear Model (GLM) with a gamma distribution and log link function was chosen (α=.05).

Results. None of the specimens showed any signs of debonding or fracture during the fatigue test. Mean ±standard deviation fracture loads ranged from 247.6 ±70.2 N (for group RM1) to 1211.5 ±243.2 N (for group RM2). A statistically significant increase in fracture resistance was observed with the increasing number of walls (P<.001). However, different CAD-CAM restorative materials did not affect the fracture resistance of endodontically treated maxillary first premolars restored with 1-piece endodontic crowns (P<.05).

Conclusions. In this in vitro study, increasing the number of remaining walls dramatically enhanced the fracture resistance of endodontically treated maxillary first premolars restored with 1-piece endodontic crowns and subjected to thermomechanical fatigue, irrespective of the type of restorative material used. (J Prosthet Dent xxxx;xxx:xxx-xxx)

The authors report no conflicts of interests.

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Clinical Implications

Regardless of the type of 1-piece endodontic crown material used, endodontically treated maxillary first premolars with 2 remaining walls can provide excellent fracture resistance.

Traditionally, the treatment for extensively compromised endodontically treated teeth (ETTs) has involved using post-and-core systems with crowns for cuspal coverage.[1–5] This approach requires preparing the post space within the root canal and coronal tooth structure, raising the possibility of weakening the tooth and perforating the root.[6,7] More recently, 1-piece endodontic crowns have gained popularity as an alternative.[8] A comprehensive clinical study[9] reported success rates ranging from 94% to 99%, with 1-piece endodontic crowns exhibiting better fracture strength than conventional restoration techniques. One-piece endodontic crowns can be fabricated from a variety of materials, including composite resins, lithium disilicate ceramics, resin-modified ceramics, and zirconia.[10] Resin-modified ceramics are an innovative form of computer-aided design and computer-aided manufacturing (CAD-CAM) ceramic material modified by resin that combines the advantages of inorganic and organic materials.[11] The impact of high-translucency zirconia and lithium disilicate was examined by Demachkia et al.[8] However, resin-modified ceramic materials were not included in the study. Furthermore, teeth with 4, 3, and 2 walls were considered in the study, but teeth with a single wall were excluded. Ahmed et al[12] investigated how the preparation design (using a ferrule or butt joint) and 2 restoration materials (zirconia and lithium disilicate) affected the ability of endodontically treated maxillary first premolars (ETPs) to withstand fractures. Nevertheless, the study excluded the impact of resin-modified ceramic materials and substance loss. The authors are unaware of data on how the biomechanical behavior of ETPs that have been restored with 1-piece endodontic crowns is affected by substance loss, raising the question: does substance loss impact the fracture resistance and failure mode of ETTs restored with 1-piece endodontic crowns made from various materials? Consequently, this study investigated how the number of remaining axial walls (1 or 2) and the choice of CAD-CAM restoration materials (zirconia, lithium disilicate ceramic, and resin-modified ceramic) affected the fracture resistance and failure mode of ETPs restored with 1-piece endodontic crowns. The null hypotheses were that the type of 1-piece endodontic crown material or the substance loss would not significantly affect the fracture resistance or failure mode of ETPs.

MATERIAL AND METHODS

Table 1 contains a list of the materials used in this investigation. After informed consent had been obtained according to the regulations of the local ethical committee, 64 human maxillary first premolars of comparable size (a maximum deviation of 10% from the means was permitted), with roots, and free of cavities, fractures, or cracks were selected. After being cleaned, the teeth were kept at 4 °C in 0.1% thymol solution. A software application (G*Power V 3.1.9.7; Heinrich Heine University Düsseldorf) was used to determine the sample size. The power of the study was determined as 82% at α=.05, which identified the need for 8 teeth per group. Using an online software application (www.randomizer.org), the teeth were assigned numbers and distributed randomly to 4 subgroups (n=8) according to the 1-piece endodontic crown materials as follows (Fig. 1): ZP: Zirconia ceramic group (IPS e.max ZirCAD Prime; Ivoclar AG); RM: resin-modified ceramic group (Katana Avencia; Kuraray Noritake Dental Inc); LD: lithium disilicate ceramic group (IPS e.max CAD; Ivoclar AG);

Table 1. Materials used

Material	Manufacturer	Composition	Batch No.
IPS e.max-CAD	Ivoclar AG	SiO2, Li2O, K2O, P2O5, ZrO2, ZnO, other and coloring oxides	YB5551
IPS e.max ZirCAD Prime	Ivoclart AG	Y2O3, HfO2, Al2O3, and other oxides	Z05357
Katana Avencia Block 2	Kuraray Noritake Dental	UDMA, methacrylate monomers, SiO2, Al2O3	001003
Panavia V5	Kuraray Noritake Dental	Bis-GMA, TEGDMA, silanated barium glass filler, silanated fluoroaluminosilicate glass filler, colloidal silica, surface-treated aluminum oxide filler, hydrophobic aromatic dimethacrylate, hydrophilic aliphatic dimethacrylate, CQ, initiators, accelerators, pigments	000149
Clearfil DC Core Plus	Kuraray Noritake Dental	– Paste A: Bisphenol A diglycidylmethacrylate(Bis-GMA), hydrophobic aliphatic dimethacrylate, hydrophilic aliphatic dimethacrylate, hydrophobic aromatic dimethacrylate, silanated barium glass filler, silanated colloidal silica, colloidal silica, dl-Camphorquinone, initiators. Pigments. – Paste B: Triethyleneglycol dimethacrylate, hydrophilic aliphatic dimethacrylate, hydrophobic aromatic dimethacrylate, silanated barium glass filler, silanated colloidal silica, aluminum oxide filler, accelerators	000041

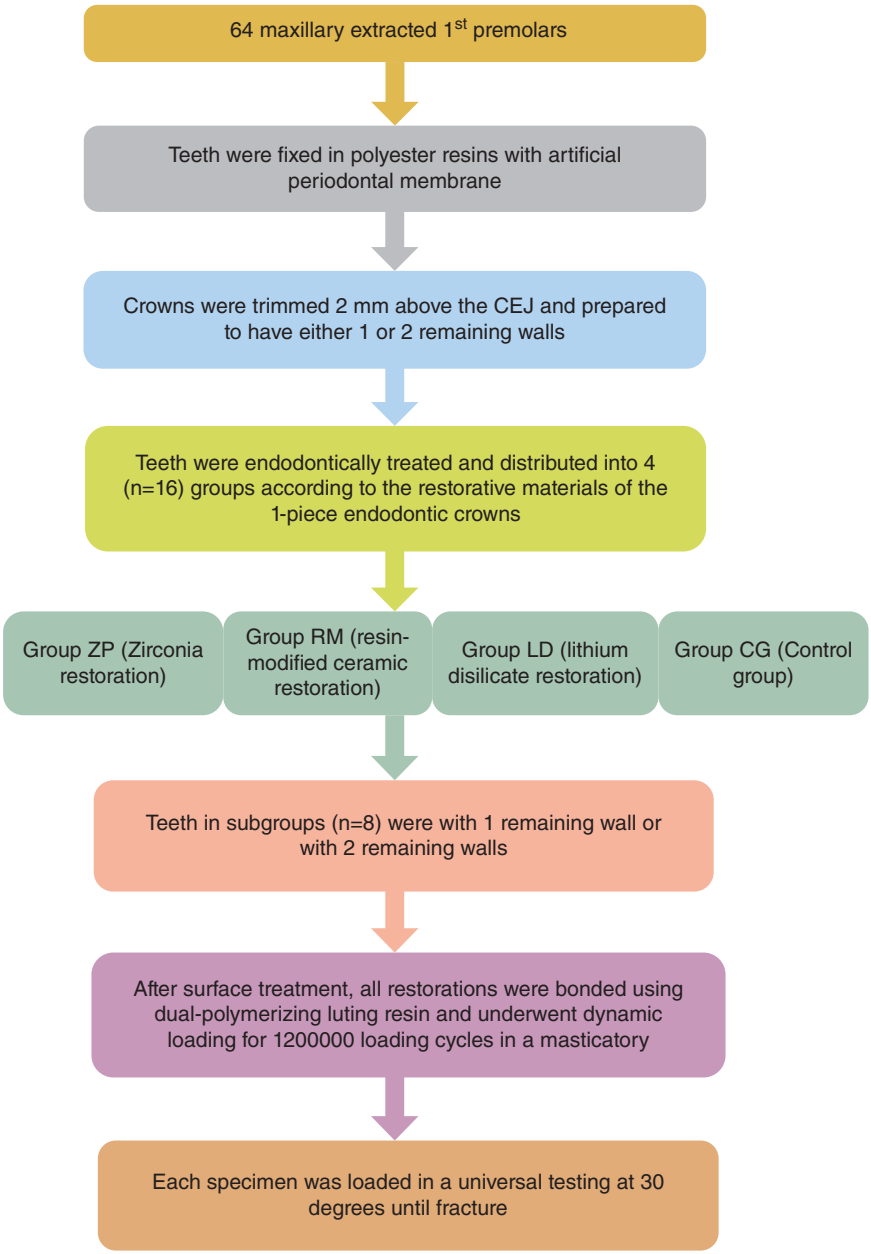

Figure 1. Flow chart of study steps.

and CG: a control group restored with zirconia posts with composite resin core buildup and lithium disilicate crowns (IPS e.max CAD; Ivoclar AG). Teeth in the subgroups had either 1 or 2 residual coronal walls (n=8). The subgroups were zirconia ceramic group with 1 wall (ZP1); zirconia ceramic group with 2 walls (ZP2); resin-modified ceramic group with 1 wall (RM1); resin-modified ceramic group with 2 walls (RM2); lithium disilicate with 1 wall (LD1); lithium disilicate with 2 walls (LD2); control group with 1 wall (CG1) and control group with 2 walls (CG2).

The access cavity was created with a high-speed, round, medium-grit, diamond rotary instrument and endodontic access burs (Komet Dental; Lemgo). The canals were instrumented to International Organization for Standardization (ISO) size 35 (S.S, K-files; Komet Dental). For obturation, a lateral condensation technique was used with gutta percha (Roeko; Coltène) and sealer (AH Plus; Dentsply Sirona). An artificial periodontal membrane (Plasti Dip; Plasti Dip International) composed of rubber was applied to the tooth roots 2 mm apically to the cemento-enamel junction (CEJ). The teeth were embedded in brass tubes with autopolymerizing polyester resin (Technovit 4000; Kulzer GmbH) up to 2 mm, apically to the CEJ, and perpendicular to the ground. A low-speed diamond disk (IsoMet 1000;

Buehler) was then used to section the crowns under coolant irrigation, parallel to the occlusal surface, and 2 mm coronal to the CEJ. After that, the mesial and distal walls (in the group of 2 buccal and lingual walls) or the mesial, distal, and lingual walls (in the group of 1 buccal wall) were cut to the CEJ level, leaving the teeth with 1 or 2 remaining coronal walls. For the 2-wall groups, the distance between them was set at 4 ±0.1 mm. The teeth were prepared internally with a divergence of 6 degrees and maintaining a wall thickness of 2 mm throughout using a tapered round-end diamond rotary instrument (Komet Dental; Lemgo) mounted to a high-speed handpiece with a rotation speed of below 160 000 rpm. The tooth preparation of the specimens was standardized by attaching the handpiece to a custom-made dental surveyor parallel to the floor. The diamond rotary instrument was replaced after 8 preparations to ensure high cutting efficacy. Using a layer of composite resin (Clearfil Dc Core Plus; Kuraray Noritake Dental Inc), the base of the pulpal floor was levelled to improve the seating of the 1-piece endodontic crown. For the control group, the palatal canals were 9 mm in length and shaped to ISO size #70 from the coronal flat surface. The zirconia prefabricated posts (ER Kit 4441.000; Komet Dental) were airborne-particle abraded with 50-μm alumina (Plurakorund; Pluradent) for 5 seconds from 10 mm at 0.1 MPa. The pretreated posts were ultrasonically cleaned for 3 minutes in 99% isopropanol (2-Propanol; Otto Fischar GmbH). The post surfaces were coated with a ceramic primer (Clearfil Ceramic Primer Plus; Kuraray Noritake Dental Inc) and dried with gentle oil-free air, while the cleaned and dried canals and dentin surfaces were treated for 20 seconds with a primer (Panavia V5 Tooth Primer; Kuraray Noritake Dental Inc) which was applied with a fine brush. Adhesive luting resin (Panavia V5; Kuraray Noritake Dental Inc) was used to bond the posts into the canals, and the excess resin was spread over the coronal base and post head and light polymerized for 20 seconds (Radii-cal; SDI Ltd). A composite resin core material (Clearfil Core DC; Kuraray Noritake Dental Inc) was then used to build up the core, and the abutment teeth were prepared, with 1 mm shoulder finish lines, to their final contour after 6 minutes.

A laboratory scanner (TRIOS Scanner; 3Shape A/S) was used to scan the abutment teeth. After that, virtual models were acquired, and a CAD-CAM software program (3Shape Software; 3Shape A/S) was used to calculate the margins. The software program (DentalCAD 3.0 Galway software; exocad GmbH) created a virtual waxing of a 1-piece endodontic crown of 6 and 5 mm occlusal thickness from the preparation butt joint to the buccal and lingual cusp tip, respectively, and 4 mm from the central groove to standardize the restoration form and occlusal anatomy across all specimens (Figs. 2, 3). After setting the luting resin space to 40 μm, the restorations were exported, saved in standard tessellation language (STL) file format, and imported and adjusted to all of the previously scanned specimens using just the "position" tools (rotation and translation) without modifying the previously saved original shape. A milling machine (Zenotec select hybrid; Wieland Dental) was used to mill the lithium disilicate 1-piece endodontic crowns and control group crowns (IPS e.max CAD; Ivoclar AG).

Following the manufacturer's recommendations, the restorations were subsequently crystallized in a ceramic furnace. The CAD-CAM milling machine (Zenotec select hybrid; Wieland Dental) was used to mill the zirconia 1-piece endodontic crowns from presintered zirconia disks (Katana Avencia, IPS e.max ZirCAD Prime, and Ivoclar AG), which were subsequently sintered in accordance with the manufacturer's instructions. In addition, the resin-modified ceramic group (Katana Avencia; Kuraray Noritake Dental Inc) 1-piece endodontic crowns were milled with the milling machine according to the manufacturers' instructions. The fitting surface of the zirconia and resin-modified ceramic 1-piece endodontic crowns groups were airborne-particle abraded with 50-μm aluminum oxide (Plurakorund; Pluradent) at 10 mm for 5 seconds at 0.1 MPa. Then, the zirconia specimens were cleaned for 3 minutes in a 99% isopropanol ultrasonic bath and air-dried, while the resin-modified ceramic was cleaned in an ultrasonic bath of distilled water for 3 minutes and air-dried. A 5% hydrofluoric acid gel (IPS Ceramic Etching Gel; Ivoclar AG) was used to etch the intaglio surfaces of the lithium disilicate 1-piece endodontic crown group for 20 seconds. After that, the etched surfaces were cleaned with water and air-dried, and a ceramic primer (Clearfil Ceramic Primer Plus; Kuraray Noritake Dental Inc) was applied on the intaglio surfaces of all crowns. All restorations were dried with a mild oil-free airflow.

Fluoride-free pumice and a rotary brush were used to clean the prepared tooth surfaces, and the outer enamel surfaces of the prepared teeth were selectively etched for 30 seconds using 37% phosphoric acid (K-Etchant Gel; Kuraray Noritake Dental Inc). After 20 seconds of application, tooth primer was applied on the prepared tooth surfaces, and Panavia V5 luting resin was used. A specially designed positioning device was used to hold each crown in place for 7 minutes while bearing a 48 N load. A light-polymerizing device (Radii-cal; SDI Ltd) with a peak light intensity of 1200 mW/cm2 was used to polymerize the luting material for 10 seconds from all directions (buccal, lingual, mesial, distal, and occlusal) after the excess resin had been removed. To find any changes in the tooth, luting resin, or 1-piece endodontic crown interface structure, all groups were examined under a ×25 magnification optical microscope (Wild

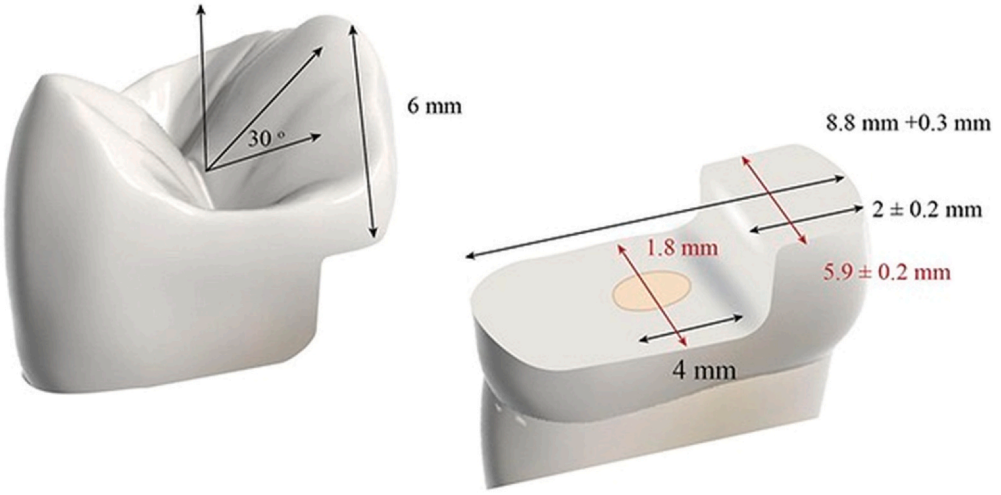

Figure 2. Preparation designs with one wall.

M420; Wild Heerbrugg). Before the thermomechanical fatigue test, all specimens were stored in deionized water at 37 °C for 3 days.

All specimens underwent 1 200 000 mechanical mastication cycles with simultaneous thermocycling between 5 °C and 55 °C in distilled water, with a 30-second dwell time at each temperature (Chewing Simulator; SD Mechatronik). The antagonists were Ø6-mm steatite ceramic balls (Hoechst Ceram Tec). Following a previous research protocol,[8] the buccal cusp was loaded vertically with a force of 48 N at speeds of 6 and 30 mm/second. All surviving specimens were examined again under the ×25 magnification optical microscope after the completion of the thermomechanical loading cycles to investigate any damage or microcracks in the tooth or restoration. In a universal testing machine (Zwick Z010/TN2A; ZwickRoell LP), all specimens that survived the dynamic loading were quasi-statically loaded at a crosshead speed of 1 mm/minute at a 30-degree angle to the tooth's longitudinal axis until fracture. The test-controlling software program (testXpert Software; ZwickRoell LP) was used to record and analyze the load necessary for the failure to occur. After the fracture test, all specimens were examined visually under a stereomicroscope at ×25 magnification (Wild M420; Wild Heerbrugg) to evaluate the failure mode and determine the fracture origin.

A Levene test was applied to assess the homogeneity of variance, indicating that the results were not homogenous ($P<.05$). Therefore, the Generalized Linear Model (GLM) with a gamma distribution and log link function was chosen ($\alpha=.05$). In addition, chi-squared

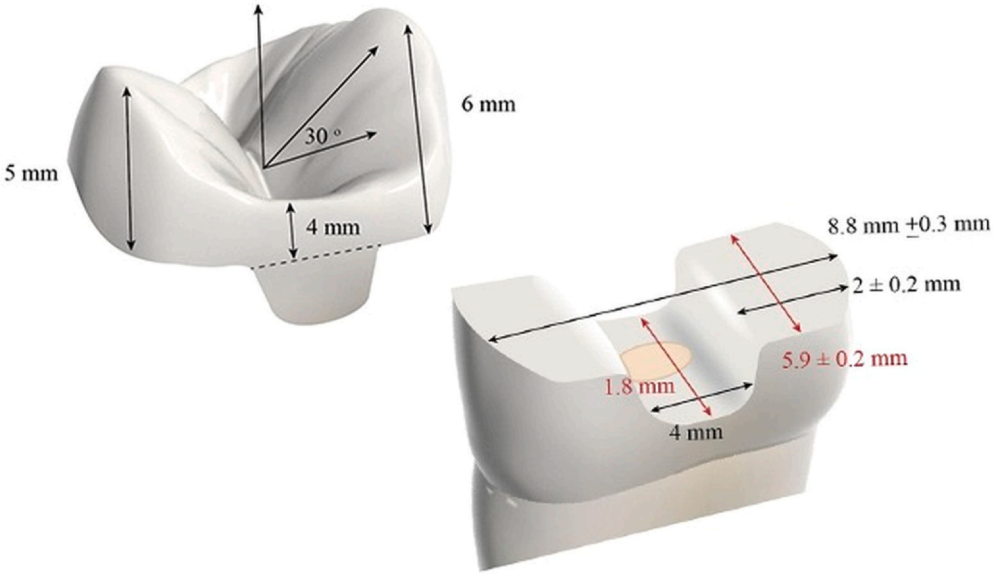

Figure 3. Preparation designs with two walls.

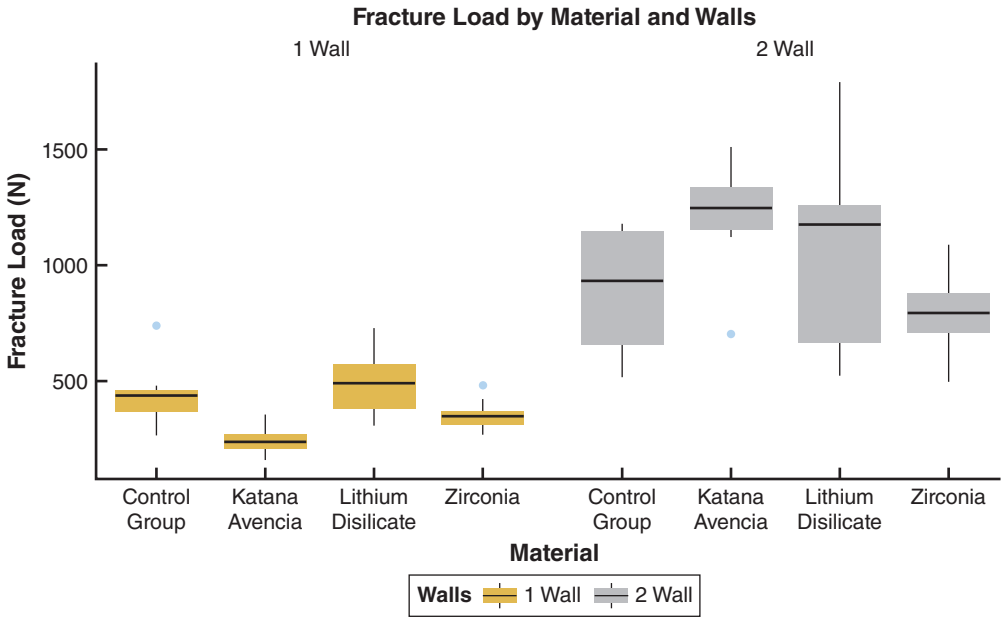

Figure 4. Fracture load values in test groups.

test of independence with post hoc test using a Bonferroni correction was performed (α=.05) to evaluate the association between failure mode and restorative material or substance loss.

RESULTS

None of the specimens failed during masticatory simulation. For the resin-modified ceramic subgroup with 1 wall, the mean ±standard deviation fracture load was 247.6 ±70.2 N, while, for the resin-modified ceramic subgroup with 2 walls, it was 1211.50 ±243.21 N. Fracture resistance was significantly higher for two walls compared to one wall (P<.001) (Fig. 4). The material, however, did not exhibit a statistically significant impact (P>.05) (Table 2). The number of walls and the fracture load were found to be significantly correlated with the GLM results, with more walls having a substantial beneficial impact; this suggests that the expected fracture load increases significantly when transitioning from 1 wall to 2 walls. In contrast, the type of material did not demonstrate significant effects on fracture load (P>.05 for all material types).

Table 2. Result of GLM comparing materials and walls using the gamma distribution log link function

Term	Estimate	SE	*t* value	*P*
Control group (Reference)				
Katana Avencia	−0.089	0.117	−0.762	.449
Lithium Disilicate	0.156	0.117	1.341	.185
Zirconia	−0.165	0.117	−1.414	.163
1 Wall (Reference)				
2 Walls	0.965	0.082	11.704	<.001

SE, standard error.

In the pairwise comparisons between groups, the Tukey adjustment with the statistical software package (emmeans, R Package; The R Project for Statistical Computing) was used for the analysis of estimated marginal means (EMMs), shedding light on how the number of walls and type of material affect fracture load. The findings demonstrate that, for all materials, the fracture load was systematically greater in teeth with 2 walls than 1 wall.

Regarding the failure mode, the modes of failure of the specimens were divided into favorable and unfavorable based on the location of the fracture line. Fractures from favorable failures were occlusal to the CEJ (restorable), whereas those from unfavorable failures were apical to the CEJ (non-restorable). Most groups demonstrated more unfavorable fracture modes than favorable ones (Fig. 5). Groups with different levels of substance loss showed statistically significant differences in fracture modes according to logistic regression analysis (P<.05). Similarly, a significant difference was observed in failure modes among groups using different materials (P<.05). Lithium disilicate and zirconia notably increased the likelihood of unfavorable failure modes compared with the control group. Additionally, 2-wall restorations were significantly more likely to result in unfavorable failures compared with those with a single wall. A logistic regression model was used to assess the failure mode. The results showed that the materials used and the number of walls both played significant roles in determining the failure mode (P<.001). In addition, chi-

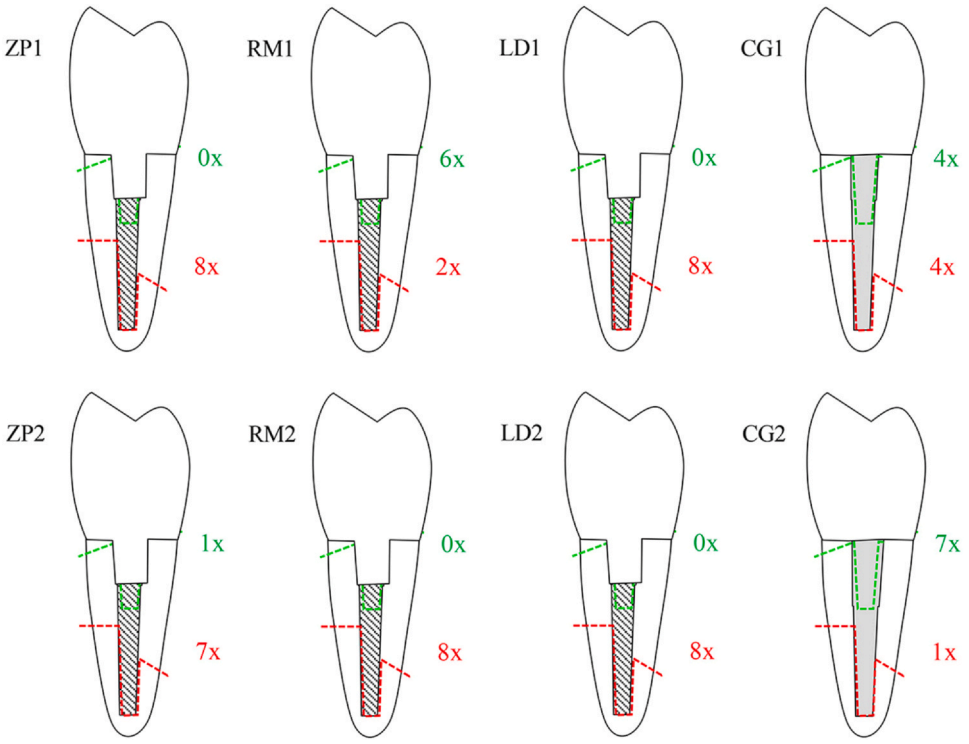

Figure 5. Fracture modes and their frequency in test groups.

squared test of independence showed a statistically significant relation between fracture mode and restorative materials (χ^2=38.03, P<.001), but not between failure mode and substance loss (χ^2=0.91, P=.78).

DISCUSSION

This in vitro study evaluated the impact of the remaining tooth structure and the 1-piece endodontic crown restoration materials on the fracture resistance of ETTs. The results of GLM analysis demonstrated that the number of remaining tooth structures (1 or 2 walls) had a statistically significant influence on the fracture resistance of ETTs (P<.001), whereas the choice of 1-piece endodontic crown restoration material did not significantly affect the fracture resistance of ETTs (P>.05). Therefore, the null hypothesis that the type of 1-piece endodontic crown material would not affect the fracture resistance of ETPs was not rejected, whereas the null hypothesis that the substance loss would not affect the fracture resistance or failure mode of ETPs was rejected. These findings highlight the critical role of remaining tooth structures in determining the fracture resistance of ETTs, providing valuable insights into the optimization of 1-piece endodontic crowns. These findings were consistent with those of previous studies that reported no statistically significant differences in the fracture resistance of ETTs when various restoration materials were used.[6,13] The increasing number of walls was associated with the higher fracture resistance of ETPs, indicating that an increased number of walls required a higher compressive load to fracture, likely because of the stronger tooth structure provided by greater remaining tooth material.[4,14,15] Therefore, the prognosis of a tooth after endodontic treatment largely depends on the amount of residual coronal dentin.[16]

This study highlights a significant interaction between the number of walls and the material type, particularly in the resin-modified ceramic group. This material showed the most substantial increase in fracture load in the presence of 2 walls (P<.001). This finding could be explained by the properties of the polymer phase within the ceramic phase, facilitated by the larger contact area between the 1-piece endodontic crown and tooth structure. Additionally, the modulus of elasticity of the resin-modified ceramic closely matches that of dentin, further contributing to stress absorption.[17] The pairwise comparisons revealed significant variations between different materials and wall groups. For example, the resin-modified ceramic group with 1 wall had a much lower fracture load than the control group with 1 wall (P<.001). These findings point to a significant interaction between the number of walls and material type, especially in the resin-modified ceramic group, which exhibited the greatest increases in fracture load in the presence of 2 walls.

Regarding the failure modes, chi-squared test of independence showed a statistically significant relation between fracture mode and restorative materials (χ^2=38.03, P<.001), but not between failure mode and substance loss (χ^2=0.91, P=.78). Lithium disilicate and zirconia restorative materials significantly increased the likelihood of an unfavorable fracture type compared with the control group, with lithium disilicate showing the strongest effect (P<.001). In the present study, the number of favorable fractures in the resin-modified ceramic group was statistically similar to that in the lithium disilicate and zirconia groups (P>.05). However, Carvalho et al[13] reported that 1-piece endodontic crown restorations made of resin nanoceramic had fewer catastrophic failures than lithium disilicate 1-piece endodontic crowns, suggesting that the lower modulus of elasticity of resin nanoceramic materials led to fewer stresses on the root.[18,19] Since zirconia is more rigid and has a higher modulus of elasticity (210 GPa) than dentin (18.6 GPa), stress accumulated inside the root results in catastrophic failures.[20,21]

Limitations of this study included the in vitro design that cannot be directly extrapolated to clinical situations. The interaction between the number of walls and material type needs further investigation with a larger number of specimens.

CONCLUSIONS

Based on the findings of this in vitro study, the following conclusions were drawn:

1. The remaining tooth structure, as indicated by the number of walls, affected the fracture resistance of ETPs.
2. The fracture resistance of ETPs was not affected by the restoration material.
3. Resin-modified ceramic materials are a promising material for the fabrication of 1-piece endodontic crowns, especially when there are 2 remaining walls available.
4. Failure mode was affected significantly by the restorative materials but not by substance loss.

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