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FEA Evaluation of the Resistance Form of a Premolar Crown

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Abstract

Purpose: The purpose of this study was to evaluate the influence of buccal and lingual wall convergence angles on the ability of the preparation to resist rotational displacement.
Materials and Methods: An intact premolar digitized by micro-CT yielded a 3D reproduction of a human tooth. Simulated crown preparations with known buccolingual axial wall convergence angles (4°, 8°, 12°, 16°, 20°, 24°, 28° 32°), sloped-shoulder marginal area, and occlusal reduction were created and restored with a ceramic crown. The tooth restoration was loaded with a 200 N force at 45° to the incline of the buccal cusp. The responses of the restored tooth with luting agents were analyzed using the 3D finite element method.
Results: This study demonstrated that a convergence angle of the preparation above 12° produced a decrease of the resistance of the crown to rotational effects. The study also showed that the use of luting agents that provide bonding between the restoration and dentine improved the rotational resistance of the crown on preparations with large convergence angles.
Conclusions: Use of buccolingual convergence angles greater than 12° reduced the resistance form of the preparation. Luting agents capable of delivering strong bonding between the crown and the preparation improved the resistance in highly tapered preparations.

Clinicians have long recognized the importance of the convergence angle between the surfaces of a crown preparation in the retention and resistance of the cemented crown. Prothero[1] was one of the first to document specific recommendations as to the acceptable range of convergence angles and suggested that 2° to 5° was ideal in 1923. Jorgensen[2] evaluated the relationship between retention and convergence angles in cemented crowns and suggested that maximal retentive forces found were at an angle of 5°.

Although retention and resistance form are different aspects of fixed prosthodontics, Prothero's[1] recommendation in 1923 for axial wall convergence is still the standard today, as presented in two recent reviews of this topic in 2001[3] and 2004.[4] Goodacre et al's[3] review of restoration resistance form illustrated the influence of various factors: tooth type/location, vertical preparation height, circumference, and the amount of preparation taper. In addition, resistance form is also emphasized in four classical fixed prosthodontics textbooks,[5-8] as recently as 2006. Goodacre et al's review[3] was considered a classic review of the "standards" in fixed prosthodontic tooth preparation at publication in 2001 and is still current in 2012.

A review of the experimental studies in the literature related to resistance form have looked at retention of gold crowns,[9] surface roughness,[10] in vitro and theoretical models, and patient fixed prosthodontic failures.[11-21] Kaufman et al[9] evaluated the resistance form of gold crowns in an in vitro experiment on metal dies to evaluate preparation height and convergence angles with and without crown perforation for vertical displacement force by retention.

Oilo and Jorgensen[10] evaluated the influence of surface roughness of the tooth preparation to retention form of crowns in 1978. Although this study only looked at vertical retention form, not resistance form, this in vitro experiment in brass cones and extracted teeth demonstrated significantly more retention in preparations with a rough surface, especially with zinc phosphate cement. The investigators suggested that the same effect would be presumed to occur in resistance form as well even though not measured in this experiment. A theoretical study by Mack[11] and in vitro studies by Potts et al,[12] Weed and Baez,[13] and Dodge et al[14] confirmed that poor resistance to displacement was present at higher levels of convergence.

Additional theoretical and actual comparisons of failed restorations to ideal standards by Nordlander et al,[15] Parker et al,[16] and Trier et al[17] demonstrated the importance of resistance form with Trier et al implicating very high deviations from theoretical standards, especially in molar preparations. Zidan and Ferguson[18] demonstrated the importance of the luting agent's ability to supplement resistance form deviations with resin cements in highly tapered preparations. A 2004 study by Proussaefs et al[19] evaluated the ability of supplemental grooves and boxes to improve resistance form in marginal preparation designs.

Chan et al[20] demonstrated that increased preparation taper improved the seatability of complete veneer crowns in an in vitro study design. Cameron et al[21] evaluated the degree of preparation taper on crown resistance to dislodgement under lateral cyclical loads until restoration failure. This investigation found that restorations placed with luting agents and cyclically loaded failed at statistically significant levels above 24° of preparation convergence, further highlighting the importance of resistance form in restoration longevity.

Finite element analysis (FEA) has been used as a theoretical tool to analyze the effects of axial wall taper on resistance form and stress to the tooth/restoration complex.[22] FEA has the advantage that variables within the sample can be manipulated by the investigators to determine changes in the model system. FEA has the disadvantage of a lack of environmental variables such temperature, bacterial invasion, and byproducts, etc. that can also influence restoration function.

Among the studies of resistance form in the literature, the three most important contributions were Parker,[4] Parker et al,[16] and Wiskott et al[22] with demonstrations of different rotational axes. Parker's[4,16] model system demonstrated an axis of rotation at the tooth/crown marginal interface, while Wiskott's[22] FEA model revealed an axis apical to the crown at the mid-root vertical location between crown margin and root apex. The location of the axis of rotation is thought to be critical to the outcome of restoration stability and its ability to resist rotational displacement in function. In summary, Wiskott's[22] rotational axis model is more favorable to restoration stability than Parker's.[4,16] This is due to an axial wall more resistant to rotation at larger amounts of taper from the long axis of the tooth.

The present FEA investigation evaluated the effect of convergence angle of a preparation on the resistance form of a human maxillary premolar, prepared within a range of both acceptable and unacceptable levels according to published guidelines. In the present study, a novel approach using 3D FEA for solving contact problems and determining the displacement of the restoration relative to the prepared tooth was used together with conventional stress-based failure analysis. The FEA of a restoration/tooth complex in very thin sections is a new look at the behavior of this mechanical system because, as yet, it has not been demonstrated in the literature.

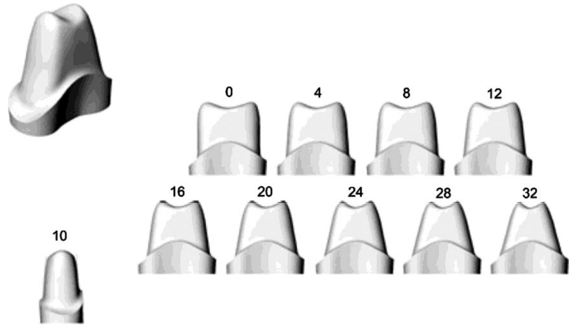

Figure 1 Examples of overall shape of preparation in perspective view exemplified here by (top left), Simulated crown preparation with rounded 120° degree sloped shoulder; (lower left), Constant 10° convergence angle of proximal walls; (right), Varied convergence angles of buccal and lingual walls.

Materials and methods

A human extracted tooth was micro-CT scanned using a SkyScan 1072 system (SkyScan, Aartselaar, Belgium). The sections were taken at 58 μm intervals, yielding a stack of 383 slices. They were then used for initial mesh generation of the surfaces and interfaces of the premolar using proprietary software. The root cementum layer was not modeled because of its small dimensions and the limited relevance for our study.

The surface meshing was followed by NURBS (nonuniform rational B-splines) conversion, thus defining the respective solid volumes. This was done by patching, using general purpose CAD software (Rhinoceros 3D for Windows; McNeel North America, Seattle, WA). The foregoing procedure created two matching bodies, one representing the enamel and the other the dentine, both in contact along the entire dentino-enamel junction. For computational efficiency the anatomic roughness of this junction, well captured on the CT reconstruction, was reduced to create a smoother junction (Fig 1). The maximum deviation between the original CT image and reconstructed surface solids was less than 0.6%. The pulp space was modeled as a void inside the dentine volume, because its Young's modulus is negligibly small compared with that of the surrounding enamel and dentine.[23]

Starting from the intact tooth, a total of nine preparations were artificially created with incremental convergence angles. The simulated preparation was done within the computer model by removing tooth structure in increments; the software allowed the investigators to remove tooth structure from the axial walls and computed the convergence angles in known amounts. The specific type of preparation was a complete crown preparation for an all-ceramic restoration in accordance with standard amounts/guidelines.[8] The buccal and lingual walls were oriented from vertical to 32°, with 2° increments per wall, by altering the geometrical determinants of the buccal and lingual walls of the preparations. The convergence angle of the proximal walls (mesial and distal) was maintained at 10° throughout all specimens (Fig 1). The cervical line of the preparation followed the natural line of the CEJ, and the rounded shoulder was uniform on all aspects of the tooth and identical in all nine models (1 mm wide, at a 120° angle to the vertical axis).

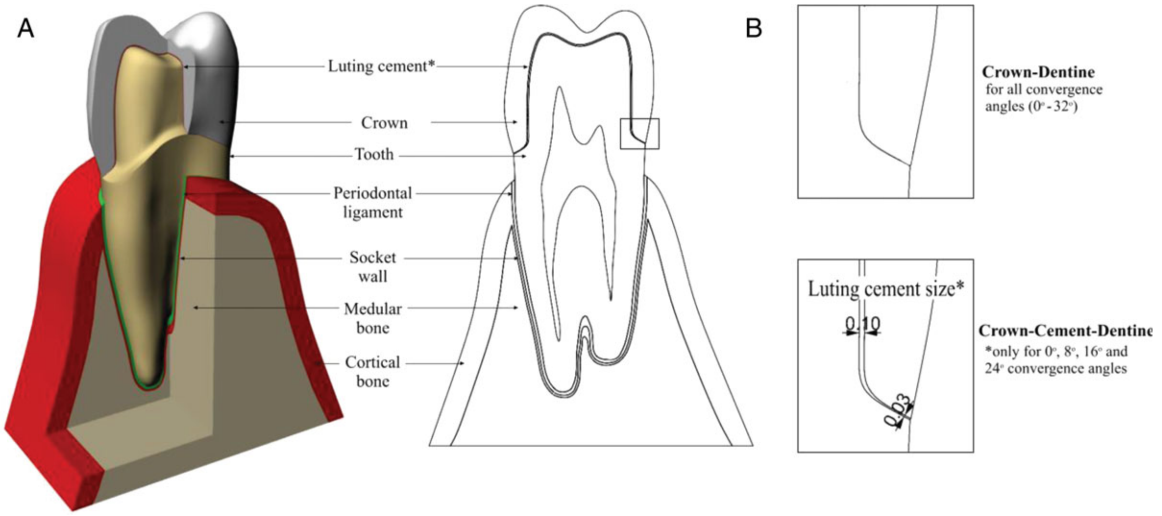

Figure 2 (A), Three-dimensional model and schematic illustration of restored tooth and its supporting structures. (B), Contact conditions between crown and preparation considered in analysis.

Identical crowns were then adapted to each of the preparations by modeling the internal aspect to fit perfectly onto the prepared shape. The crown thickness in the cervical area was 1.4 mm, corresponding to a standard crown; however, the thickness above cervical level increased with the convergence of the preparation. Each of the nine prepared teeth was embedded into an identical simulated alveolar process. This consisted of a 1-mm thick cortical bone layer that enclosed the volume of trabecular bone, both accommodating the corresponding tooth socket. The socket was lined with a 0.1-mm thick layer of denser material to simulate the socket wall, to which the tooth was connected via a 0.3-mm thick material to simulate the periodontal ligament. This detailed representation of the supporting structure was aimed at creating a more realistic anatomical model system for our numerical evaluation (Fig 2A).

In addition, four of the models with convergence angles of 0°, 8°, 16°, and 24° were duplicated, and a luting cement layer was modeled between the crown and the preparation in the duplicated models. The thickness of the luting agent was taken at 100 μm on the axial walls and 30 μm on the marginal areas (Fig 2B).

In clinical situations, a die spacer is used to preserve the volume for the luting agent, and hence the crown does not directly contact the underlying dentine; however, in this study, investigating the resistance feature of the different convergence angles, the investigators considered a direct frictionless contact between the internal surfaces of the crowns and the preparation. Under such a contact condition, the crown can move away from the preparation under the deflective loading, having the geometry of the preparation as the sole determinant of the displacement. This procedure aimed to highlight only the resistance provided by shape of the preparation.[3] The ability of the crown to move away from the preparation provided an indication of the potential crack opening displacement at the margin. As such, the greater this opening, the higher the driving force for crack extension under occlusal loading.

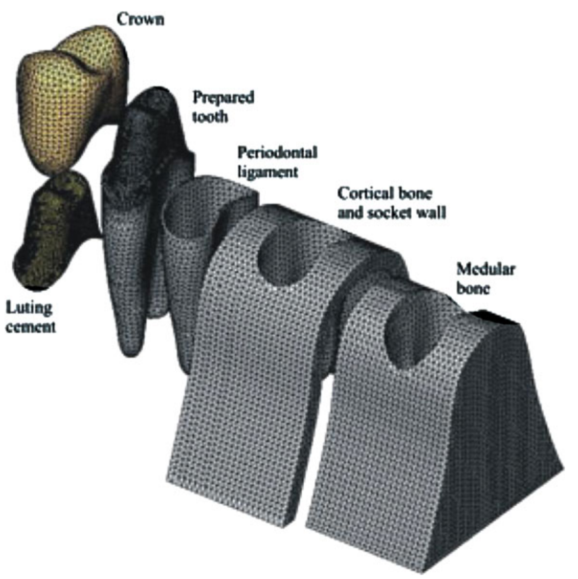

Figure 3 Meshed assembly exemplified by components of 24° preparation.

For investigating tensile stresses developed in the luting cement, only four of the convergence angles were considered, namely the 0°, 8°, 16°, and 24° preparations. These models accommodated a luting cement layer between the crown and dentine. Employment of only four convergence angles was based on the results obtained in investigating the resistance feature of the preparations. The effect of modern luting agents (resin-modified glass ionomer cements [RMGI] and resin-based cements) was simulated by considering a bonded relationship between the crown, the luting cement, and the underlying dentine.

Table 1 Modulus of elasticity and Poisson's ratio values used in the analysis for each component of the model system (Ruse,[26] Ichim[23])

	Modulus of elasticity	Poisson's ratio
Dentine[23]	14.7 GPa	0.3
Periodontal ligament[26]	3×10^{-5} GPa	0.45
Bone[23]	14 GPa	0.3
Resin-modified glass ionomer[30]	10.8 GPa	0.3

The geometrical models were then imported into general-purpose FEA software (COSMOS Design/STAR, Dassault Systemes SolidWorks Corp., Concord, MA) and meshed using parabolic tetrahedral elements (high-order elements). The element size for the periodontal ligament was 0.3 mm, while the remainder of the model was meshed using 0.5 mm elements. In the featured models, the cement layer was meshed with 0.1 mm elements. Adaptive-feature meshing was employed to ensure appropriate size in the small areas of the models. The meshing process yielded an average of 350,000 elements per model (Fig 3). A mesh convergence test was carried out for each of the models to ensure that the numerical solution was convergent and no further refining of the mesh was required. To simulate a destabilizing occlusal contact on the crown, a 200-N force oriented at 40° to the vertical axis of the tooth was applied over a 2.5 mm^2 area on the lingual incline of the buccal cusp. The model was fixed on the sectional surface of the alveolar support (Fig 2).

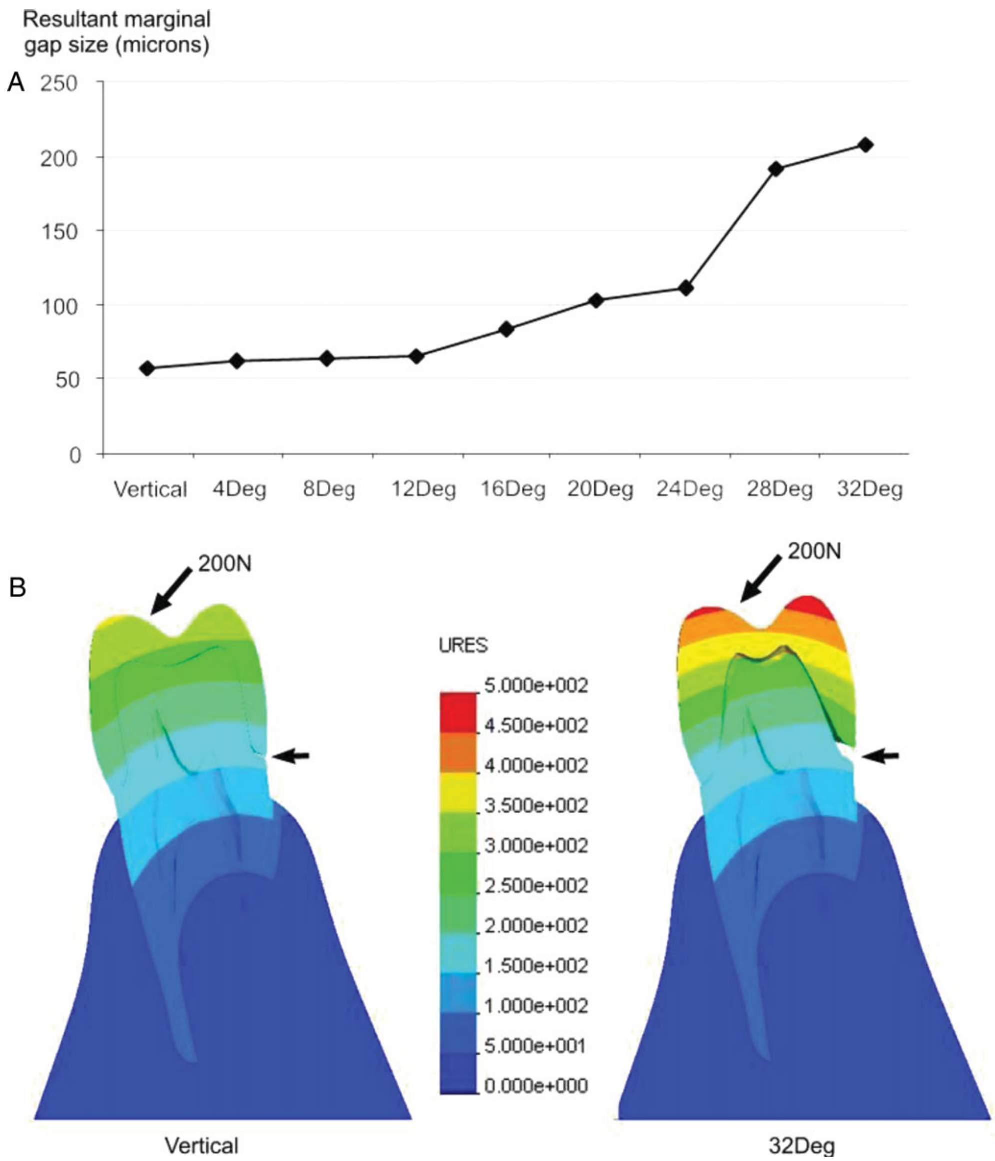

Figure 4 Comparison of calculated resulting displacements (μm) at palatal margin of crown. (A), Section plots. (B), Exemplifying resulting displacement of vertical and 32° model (deformations scale 5×). Note changes in elliptical radius of displacements towards apical as result of tooth flexure.

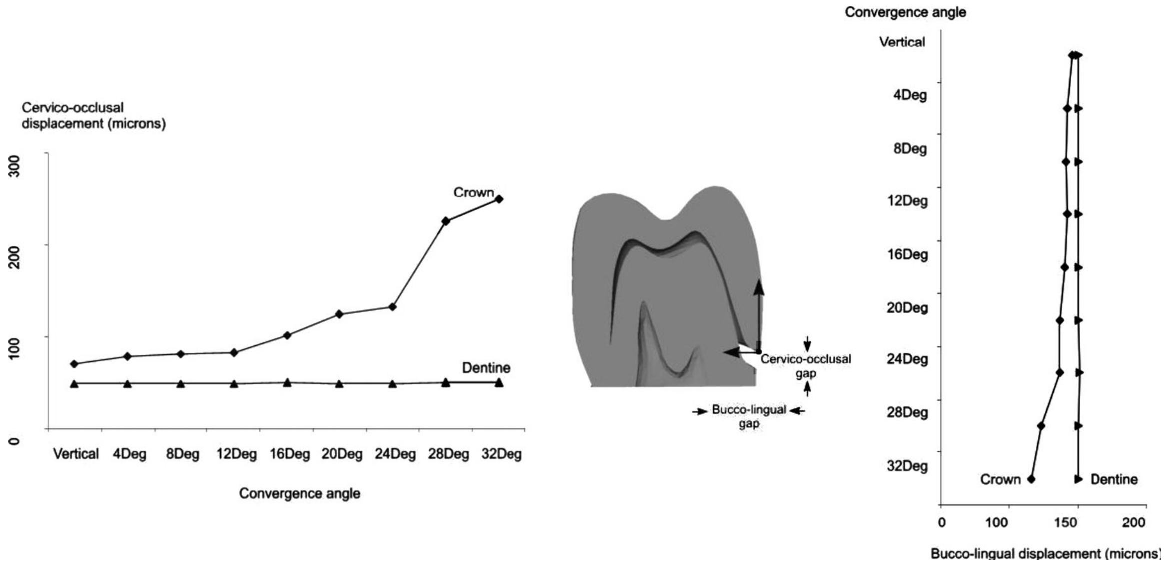

Figure 5 Comparison of calculated displacements at palatal margin as described by their components: cervico-occlusal and buccolingual.

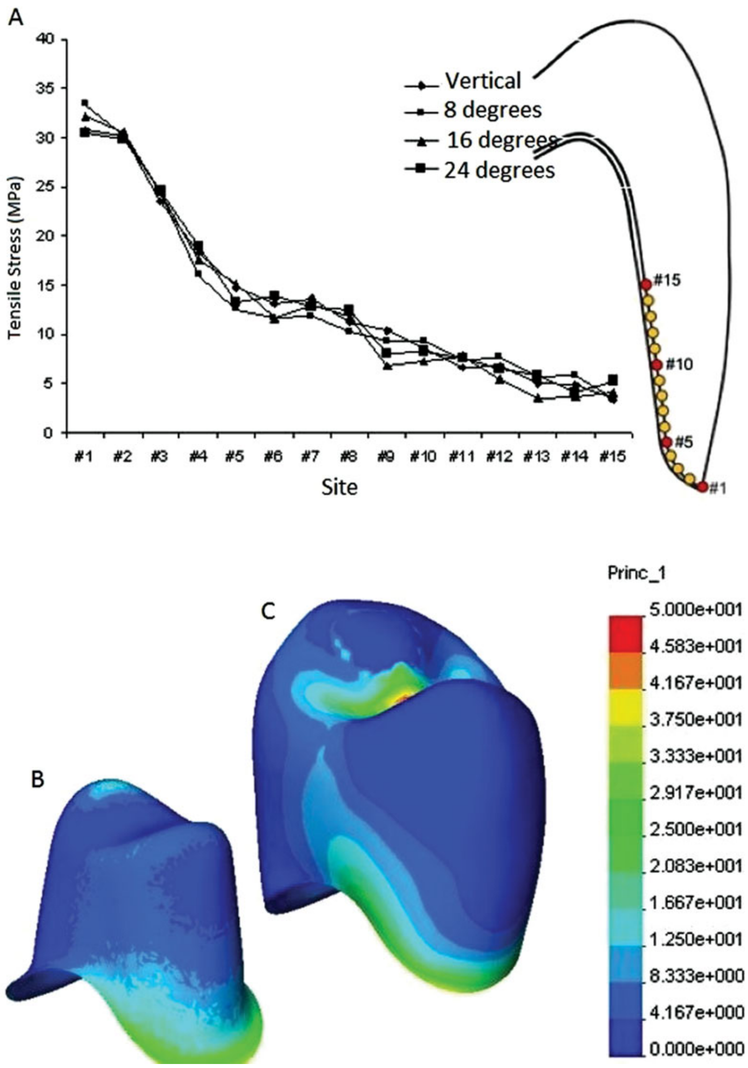

Figure 6 Tensile stress profile along palatal interface for considered: (A), Convergence angles with RMGI cement as luting agent; (B), Plots showing tensile stress distribution on cement layer; (C), Plots showing tensile stress distribution on crown.

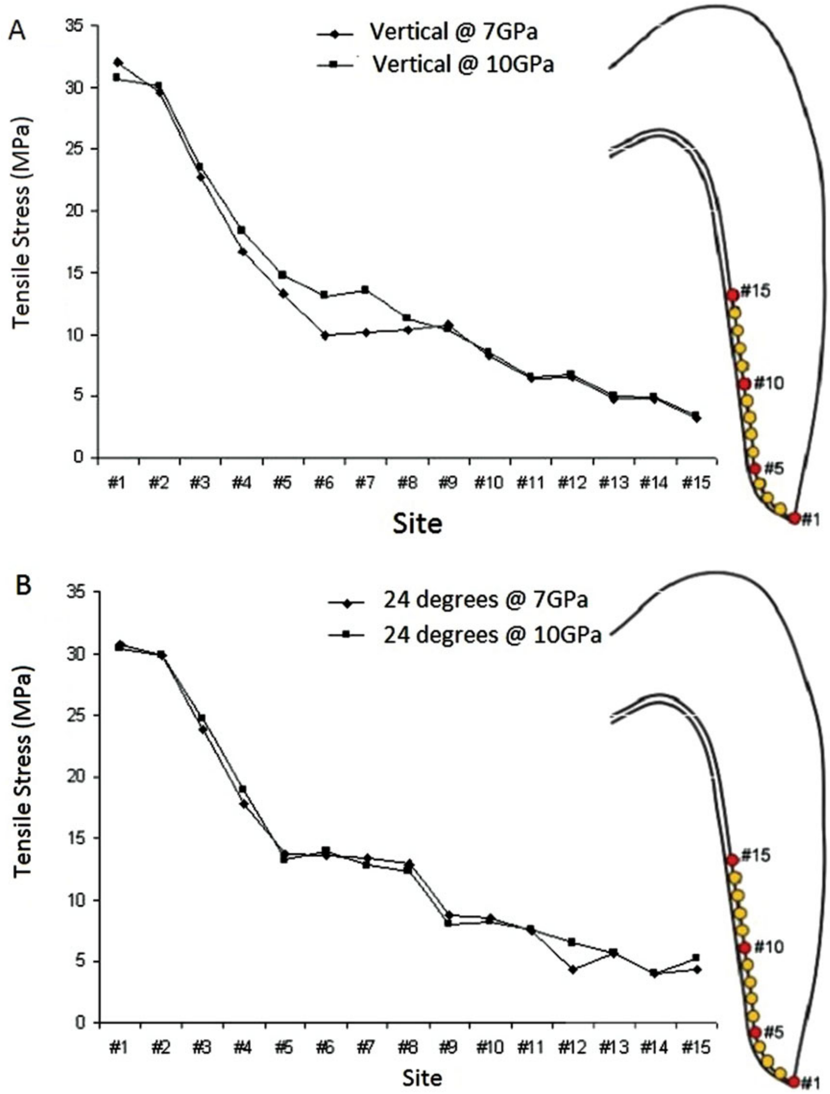

Figure 7 Comparative plots of tensile stress along palatal interface for luting agents with different elastic properties for vertical discrepancies: (A), 0° preparation; (B), 24° preparation.

Isotropic homogenous material properties were assigned for all the components of the numerical model, as described in the literature. It is known that the tooth structure components, that is, dentine and enamel, are made of nonhomogenous and anisotropic materials, but the regional property variation is restricted to a microscopic scale, a severe limitation. Real physical specimens have repeatedly shown that tooth substance behavior is elastic during physiologic function.[24,25] The dentine component of the model was assigned an elastic modulus of 14.5 GPa and Poisson's ratio of 0.3. The periodontal ligament was assigned an elastic modulus of 3×10^{-5} GPa and Poisson's ratio of 0.45.[26] A summary of these values for the components of the model can be seen in Table 1. The crown was taken as being manufactured out of ceramic with an elastic modulus of 200 GPa and a Poisson's ratio of 0.19.[27]

Two elastic moduli were considered at the highest and lowest end of the scale for the existing adhesive luting agents: 7 GPa for resin-based cements, 4 GPa for RMGI cements.[27] The analysis was carried out using a nonlinear solver embedded in commercial FEA software (COSMOS Design/STAR). Each component within the FEA model is elastic, but a nonlinear solution had to be used due to the movement of the crown away from the tooth as the crown was loaded at 200 N.

To assess the influence of the convergence angle, the calculated displacements of the crown were plotted, and numerical values collected and contrasted for each preparation shape. The numerical values were recorded at the lingual margins of the crown and of the preparation as described by their orthogonal components. These values showed the displacement in cervico-occlusal and buccolingual directions. The difference between the displacements of the crown margin and preparation margin in a vertical direction was interpreted as the resulting marginal gap. For the assessment of the principal tensile stresses, the values were collected at 15 points equally spaced at 0.3-mm increments along the axial line of the cement/crown interface on the lingual aspect.

Results

The resulting data showed that as the convergence angles increased to higher angles, restoration margin displacement increased. Preparation angles between vertical and 12° yielded the smallest displacement of the crown at the palatal margin. Preparation angles of 16° to 24° caused a larger displacement of the crown, whereas convergence angles above 24° generated very large displacements of the crown (Fig 4).

The components of direction of the crown's cervical margin displacement were strongly influenced by the convergence angle (Fig 5). In the cervico-occlusal direction, that is, vertical, the 0° preparation demonstrated the smallest displacement of the crown margin (70 μm). Convergence angles of 16° and 24° demonstrated a larger vertical crown margin displacement of 100 μm to 133 μm. Convergence angles greater than 24° demonstrated a steep increase in vertical gap size with the largest at 250 μm for the 32° preparation.

In a buccolingual direction, an inverse relationship between convergence angle and displacement was observed (Fig 5). The largest displacement in this category was recorded in the vertical preparation (146 μm), but this was very close to the displacement of the dentinal margin (151 μm), hence resulting in a reduced marginal gap. In contrast, the 32° preparation demonstrated the smallest displacement of the crown in a buccolingual direction (115 μm), while the displacement of the dentinal margin remained virtually unchanged (150 μm), resulting a larger marginal gap.

Mapping of principal tensile stresses along the cement/crown interface showed a remarkable consistency despite the different convergence angles considered (Fig 6). There was a consistent pattern of the stresses with the highest values of 30 MPa to 33 MPa recorded on the margin of the crown. From this marginal point, the stresses decreased rapidly along the shoulder and then more slowly along the axial walls (Fig 6).

Comparison of two elastic moduli (E) of the materials considered showed a minimal influence of the luting agent in the stress profiles recorded on the palatal interface (Fig 7). The 0° vertical preparation was the only demonstration of a small tensile load reduction of 4 MPa at the base of the axial wall (Fig 7A, #6 and #7). By contrast, the 24° preparation tensile loads were remarkably similar in their values and pattern.

Discussion

In this study, the investigators used a numerical analysis to determine the influence of convergence angle on the resistance form of a premolar crown preparation, and the results highlight two interrelated factors that concur at obtaining an increased resistance of the restoration-resistance form. First, resistance form was strongly influenced by the convergence angles of the preparation—it decreases with a widening of the angle of convergence. This is consistent with other studies that showed experimentally that an increase in convergence had a negative impact on the resistance of the crown.[12-20] In everyday practice, although it may be difficult to strictly control the angulations of axial walls, single wall angulations from 2° to 5° have been recognized in the literature to be acceptable;[1-20] however, to supplement compromised resistance form, the use of grooves or boxes has been recommended.[3,6,21]

Although the angulations and level of stress used in this study's analysis may represent severe levels of stress patterns found in bruxing patients, these values provided useful data in understanding the failure mechanics of the luting agent. One should consider multiple factors when analyzing the mechanical causes of failure: the predominant type of stresses (e.g., tension or shear) and their location, the cohesive and adhesive strength of the materials, as well as their fracture toughness, and other factors that may assist failure's progression by maintaining an elevated level of stress. The current investigation has shown that tensile stresses are highest on the lingual shoulder and decrease on the axial walls of the preparation.

The values of the tensile stresses are above or at the upper limit of the ultimate tensile and bonding strengths of the RMGI and resin-based cements (e.g., 10-20 MPa for RMGI, 35 MPa for resin-bonded luting agents).[27] By contrast, the shear stress values on the palatal shoulder are very small. This indicates that mechanical failure of the luting agent for a given load case is likely due to tensile stresses and likely to initiate at the margin of the crown. Once the failure has been initiated in the cement or at the interface, it will propagate along the shoulder driven by the steep tension gradient. With the occurrence of debonding, the crown's palatal margin would be free to move slightly away from the substructure as the tooth and crown flex under occlusal load. In turn, this flexion increases the tension in the luting cement, thus possibly increasing crack propagation stress.

When the separation extends along the axial wall of the preparation, the convergence angle becomes important in assisting the debonding. The investigation has shown that the degree of displacement of the crown increases with the convergence angle, and as such, a crown whose rotation is not opposed by the geometry of the preparation would generate a higher tensile stress in the luting agent, thus assisting failure during bite-induced cyclical loading of the crown. Although the force levels used in this investigation may represent the extremes of bruxing and eccentric occlusal loading, the same trends may be expected at reduced force levels to a lesser degree.

One can argue that once the crack propagates along the interface, oral fluids can enter the cracks and facilitate crack propagation because of their incompressibility.[28] Furthermore, oral fluids are known to be corrosive,[29] and the cyclic openings together with the stress concentration and damage will weaken the local material strength and accelerate degradation of the material, whereas at the same time enhancing the action of other nonmechanical factors, like hydrolytic dissolution and chemical corrosion. These findings may help explain the clinically and experimentally observed failures of crowns, particularly those with wide taper angles. The gradient may change with each incremental failure propagation along the cemented interface, and it should be noted the current analysis may be speculative.

Furthermore, it also helps understand the better clinical efficiency of resin-based luting agents, which benefit from an increased tensile strength and fracture toughness. In turn, these qualities will reduce the likelihood for the crack to initiate and also will resist its propagation along the interfaces, hence strengthening the restoration, even in wide-convergence preparations.

Once the debonding extends on the palatal interface, it will reflect on the stress profile on the buccal side; however, because the cohesive or interfacial crack propagation is a dynamic process that attracts dramatic changes in the stress profiles, an in-depth failure analysis cannot be achieved using linear models. We suggest that further work that employs elements of fracture mechanics and advanced models is beneficial to understanding the failure mechanisms.

A final point is that our results should be interpreted within the limitations and assumptions of the numerical modeling. The assumption regarding the material properties (i.e., isotropy and homogeneity) may not fully represent the real structure. Also the supporting bone was not modeled after CT. Hence, this may influence the results, even if the tooth's support was chosen to replicate the in vivo recorded mobility of the tooth; however, FEA is shown to produce valuable results and to provide biomechanical insights otherwise very difficult to achieve and compliments excellent experimental work that validates the method. Nonetheless, this study provided a biomechanical rationale enabling a better understanding of mechanical implications of wide convergence angles and furthermore provides practical suggestions of means to compensate their negative influence.

The present investigation's FEA model demonstrated findings similar to Wiskott et al's,[22] with the rotation axis within the supporting bone or the root area, not at the restoration/tooth finish line interface area as depicted by Parker et al's investigational model system.[16] The current rotational axis with the resultant forces would be presumed to be more favorable than the restoration/tooth finish line interface axis.

Conclusions

In this study, the investigators used numerical analysis to determine the influence of taper angle on the mechanical resistance of crowns. Within the limitations of this study, the authors concluded:

(1) Destabilizing contacts for unbonded interfaces cause marginal gaps at all convergence angles, but the size of the gap at small preparation taper angles were lower. Use of buccolingual convergence angles greater than 12° reduced the resistance form of the preparation.
(2) Luting agents able to deliver strong bonding between the crown and the preparation help compensate for the reduced resistance of a preparation with wide convergence angles.
(3) The stress patterns with a 200 N angled force on the inner incline of the buccal cusp of a natural human premolar demonstrated projections of concentric bands apically into the root and supporting bone rather than a rotational axis at the crown's margin.

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