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Influence of crosshead speed on failure load and failure mode of restored maxillary premolars

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Abstract: We analyzed the effect of the crosshead speed of an applied load on failure load and failure mode of restored human premolars. Fifty intact, noncarious human premolars were selected. Class II mesio-occlusodistal preparations were made with a water-cooled high-speed preparation machine, and the teeth were restored with composite resin. The specimens were divided into five groups (n = 10 each) and tested individually in a mechanical testing machine, in which a 6.0-mm-diameter steel cylinder was mounted to vary the crosshead speed: v0.5: 0.5 mm/min; v1: 1.0 mm/min; v2.5: 2.5 mm/min; v5: 5.0 mm/min; and v10: 10.0 mm/min. The cylinder contacted the facial and lingual ridges beyond the margins of the restorations. Peak load to fracture was measured for each specimen (N). The means were calculated and analyzed with one-way analysis of variance followed by Tukey's test (α = 0.05). The mean load at failure values were (N) as follows: v0.5, 769.4 ± 174.8; v1, 645.2 ± 115.7; v5, 614.3 ± 126.0; v2.5, 609.2 ± 208.1; and v10, 432.5 ± 136.9. The fracture modes were recorded on the basis of the degree of the tooth structural and restorative damage: (I) fracture of the restoration involving a small portion of the tooth; (II) fractures involving the coronal portion of the tooth with cohesive failure of the composite resin; (III) oblique tooth and restoration fracture with periodontal involvement; and (IV) vertical root and coronal fracture. Varying crosshead speeds of 0.5–5.0 mm/min did not influence the failure load of restored maxillary premolars; however, increasing the crosshead speed to 10 mm/min decreased the failure load values and the degree of tooth structural damage.

Keywords: Composite Resins; Dentin; Tensile Strength; Biomechanical Phenomena; Dental Enamel.

Introduction

Laboratory mechanical tests of restored teeth are usually conducted to evaluate restorative materials and techniques. These tests present meaningful parameters to predict the relationship between the tooth structure and restoration.[1,2] Experimental methods are important to predict failures in restorative material, tooth structure, or in the interface between them by quantifying factors related to the strength of the restored teeth.[3] In contrast, these tests do not fully simulate the complex oral environmental conditions because dental failures primarily occur due to fatigue.[4]

Several experimental methods are employed to analyze the load application mode on the tooth and involve generating stress, failure mode, and failure load.[3] However, the loads usually applied in fracture tests could exceed those verified during normal movements of the stomatognathic system.[5] A laboratory test situation could be compared to an intense load, such as when a small solid body is bitten and the concentration of force occurs at a single point on a tooth and is then distributed among the occlusal surfaces of the posterior part of the tooth.[6] Therefore, some crucial factors must be considered when conducting mechanical tests, such as the method and material used for embedding the teeth,[7] variability in dental anatomic details,[8] and the sample storage media.[9]

In addition, large variations in crosshead speed during testing and load application apparatus have been reported.[10] Some authors analyzing the mechanical behavior of the posterior teeth conducted the test by applying different crosshead speeds of 0.5 mm/min,[4,7,11] 1 mm/min,[12,13] 5 mm/min,[14,15] and 10 mm/min;[16] thus, a comparative analysis of fracture data among studies has been described.

Therefore, the aim of this study was to investigate whether different crosshead speeds interfere with the failure load results of maxillary restored premolars. The null hypothesis tested was that increasing crosshead speed does not influence fracture resistance or failure mode of human maxillary premolars with the mesio-occlusodistal (MOD) cavity restored with composite.

Methodology

Tooth selection and simulation of periodontal ligaments

Fifty premolars with similar dimensions (coronal volume within 10% of the mean) were selected. Roots without curvature, free of cracks or defects, and stored for no longer than 3 months were the standardized parameters. Root anatomy was also standardized as proposed by Soares *et al*.[17] This study protocol was approved by the Ethics Committee for Research at the Federal University of Uberlândia, MG, Brazil (#058/05). Calculus and soft tissue deposits were removed with a hand scaler (Hu Friedy, Chicago, USA). The teeth were cleaned using a rubber cup and fine pumice water slurry and stored in 0.2% thymol solution (F. Maia Ind. Com., Cotia, Brazil) at 37°C for less than 3 months.

The roots were dipped into melted wax up to 2 mm below the cementum-enamel junction (CEJ), resulting in a 0.3 mm thick wax layer. X-ray film (Kodak, New York, USA), with a centralized circular 5 mm diameter hole, was used to stabilize the teeth for the embedment procedure, as described previously.[7] The sets were positioned downward over a perforated wood plate to embed the teeth 2 mm away from the CEJ. Polyvinyl chloride cylinders (25 mm in diameter; Tigre, Rio Claro, Brazil) were positioned, fixed with wax, and filled with cold-cure polystyrene resin (Aerojet, São Paulo, Brazil). After the resin polymerized, the teeth were removed from the cylinder, and the wax was removed from the root surface and resin cylinder. Polyether impression material (Impregum F; 3M Espe, St. Paul, USA) was placed in the resin cylinders to simulate the periodontal ligament.[7] The tooth was then reinserted into the cylinder, and excess elastomeric material was removed with a scalpel blade (Xishan Medical Instrument factory, Xishan, China).

Cavity preparations

A MOD cavity with internally rounded angles was prepared in each tooth using a 6° tapered diamond rotary cutting instrument (#1151; KG Sorensen, Barueri, Brazil). A custom-made preparation machine[6] was used to standardize the cavity dimensions. The device consisted of a high-speed hand piece coupled to a mobile base, which moved vertically and horizontally with 0.1 mm accuracy digital micrometers (Mitutoyo, Tokyo, Japan). The isthmus floor of each cavity was prepared to one-third of buccal-lingual width; the pulpal floor was prepared to a depth of 2.5 mm away from the cavo-surface margin, and the bucco-lingual widths on the mesial and distal boxes were similar to the occlusal isthmus width. Each box had a gingival floor depth of 1.5 mm and an axial wall height of 2 mm. Margins were prepared with a 90° cavo-surface angle.

Restorative procedures

The cavity preparations were etched using 35% phosphoric acid (Scotchbond Etchant, 3M-Espe) for 15 s, rinsed with an air-water spray for 15 s, and blotted dry with absorbent paper. Two consecutive coats of Adper Single Bond 2 adhesive system (3M-Espe) were applied to the tooth using a fully saturated brush tip, followed by gentle air-drying for 5 s and light activation with a quartz-tungsten-halogen curing unit (XL3000, 3M-Espe) for 20 s at 800 mW/cm^2 irradiance and a 1 cm source to-specimen distance. A metal matrix band held with a retainer was placed around the tooth for the incremental restorative technique, and each increment of the microhybrid resin composite Filtek Z250 (3M ESPE) was light-activated for 20 s. Then, the sample were stored for 24 h in distilled water at 37°C, finished with a fine diamond bur (KG Sorensen) at low speed with air-water spray cooling, and polished using an aluminum oxide disc (Sof-Lex system, 3M ESPE).

Fracture resistance test

The specimens were divided randomly into five groups (n = 10 each) according to the crosshead speed used for applying the load during the fracture resistance test: v0.5, 0.5 mm/min; v1.0, 1.0 mm/min; v2.5, 2.5 mm/min; v5.0, 5.0 mm/min; and v10, 10.0 mm/min. The restored teeth were subjected to axial compressive loading using a 6 mm diameter metal cylindrical plunger in a mechanical testing machine (DL2000; EMIC, São José dos Pinhais, Brazil). The plunger was positioned in contact only with the tooth structure and did not touch the restorative material. The force required (N) to cause a fracture was recorded by a 5-kN load cell hardwired to software (TESC; EMIC), which detected any sudden load drop during compression.

Fracture resistance data were submitted to one-way analysis of variance (ANOVA) followed by Tukey's Honestly Significant Difference test at a significance level of $p < 0.05$. Additionally, a non-linear regression analysis was carried out to investigate the relationship between crosshead speed for applying the load and fracture resistance. The fractured specimens were evaluated to determine the fracture patterns using a modified classification system based on the classification proposed by Burke *et al.*:[4] (I) fracture of the restoration involving a small portion of the tooth; (II) fracture involving coronal tooth portions and cohesive failure within the composite; (III) oblique fracture with periodontal involvement; and (IV) vertical root and coronal tooth fracture.

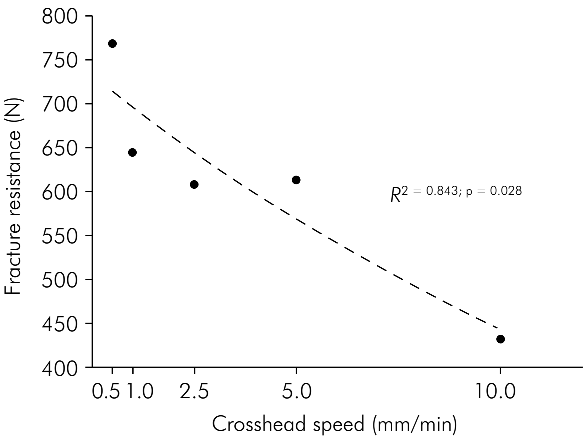
Results

The Kolmogorov–Smirnov test showed that the data followed a normal homogeneous distribution. The one-way ANOVA revealed differences in fracture resistance among groups according to crosshead speed used during the compression test ($p = 0.001$, Table). The mean premolar fracture resistance values tested with crosshead speeds of 0.5-5.0 mm/min were similar. When the test was conducted at a 10 mm/min crosshead speed, significantly lower fracture resistance was observed, compared with that at the 0.5 mm/min ($p = 0.000$) and 1.0 mm/min ($p = 0.030$) speeds, but was not different from the 2.5 mm/min ($p = 0.102$) or 5.0 mm/min ($p = 0.087$) speeds. In addition, the non-linear regression model (Figure) was significant ($p = 0.028$), showing that an increase in crosshead speed predicts a decrease in

Table. Means (standard deviations) for fracture resistance (N) and distribution of failure modes.

Crosshead Speed	Fracture Resistance	Failure Mode			
		Type I	Type II	Type III	Type IV
0.5	768 (175)[a]	10%	-	70%	20%
1	644 (116)[a]	10%	20%	40%	30%
2.5	608 (208)[ab]	10%	50%	40%	-
5	613 (126)[ab]	20%	-	80%	-
10	432 (136)[b]	20%	70%	-	10%

Means followed by distinct letters are significantly different (Tukey's HSD test, $p < 0.05$).



The non-linear regression model was significant (p = 0.028), indicating that an increase in crosshead speed can predict a decrease in the fracture resistance of adhesively restored premolars (R^2 = 0.843).

Figure. Non-linear regression model.

fracture resistance of adhesively restored premolars (R^2 = 0.843). A description of the failure analysis is shown in Table. A greater number of severe failures (types III and IV) occurred when the compression test was conducted at lower crosshead speeds. In contrast, use of the 10 mm/min speed tended to decrease the number of severe failures.

Discussion

The null hypothesis tested was rejected. Increasing the crosshead speed influenced fracture resistance and the failure mode of human maxillary premolars with a MOD cavity preparation restored with composite. The overall analysis (Figure) indicated a tendency for reduced fracture resistance when higher crosshead speed loads were applied. Performing the mechanical test with a 10 mm/min crosshead speed decreased fracture resistance and also decreased the severity of the failure pattern, otherwise the 0.5–5.0 mm/min crosshead speed outcomes were similar.

Fracture is defined by the point when stress intensity reaches or exceeds a critical value prompting rupture.[10] Although teeth are covered by enamel, which is a brittle tissue,[18] it is underlayered by dentin, which has ductile behavior.[19] In addition, the periodontal ligament can deform and accommodate the tooth in the alveolus, which alleviates stress in the cervical region of the tooth. In this experiment, a polyether impression material was used with polystyrene resin to simulate a clinical fracture resistance test.[7]

Structures with ductile characteristics tend to be brittle when submitted to higher crosshead speed load applications.[20] As we observed, samples loaded at the 10.0 mm/min crosshead speed presented about 44% less fracture resistance compared to samples loaded at 0.5 mm/min. The loose ductile characteristics could be attributed to the lower ability of the structure to dissipate stress at higher crosshead speeds. The microstructure was unable to reorganize, *i.e.*, impacting a load over the structure does not allow interatomic and intermolecular rearrangement, even in a plastic manner, as overloading the structure causes premature rupture.[21] The fracture resistance test was unable to detect a difference in fracture resistance between the experimental groups loaded with crosshead speeds < 5.0 mm/min. Perhaps, other approaches using different methodologies, such as dynamic finite elements analysis or the strain gauge method, would provide more accurate measurements of strain and rupture.

In addition to discussing fracture resistance values, it is important to analyze the fracture modes in each experimental group.[6] We observed that increasing the load application speed to 10 mm/min induced fewer catastrophic failures (Table). We hypothesized that crosshead speeds of 0.5–5.0 mm/min allowed a better stress distribution inside the restored tooth. Thus, a high concentration of energy did not occur in a small portion of the sample body, permitting higher deformation along the specimen resulting in more catastrophic failures.[21] In this context, it is proposed that crosshead speed should be < 5.0 mm/min when the goal is to allow intermolecular rearrangement and fatigue to a load. In contrast, if the objective is to simulate the impact on a structure, crosshead speeds ≥ 10.0 mm/min should be used *i.e.*, the bracket removal test or resistance test of acrylic resins based on polymethyl methacrylate.

It is not proper to compare results between different studies that employed distinct crosshead speeds on fracture resistance tests because it can influence the results, as shown here. This study has indirect clinical relevance. Therefore, any comparison between studies that used this methodology and could guide clinical protocols should be aware of this methodological parameter. Another study also showed that the type of load application device significantly influences the behavior of the tooth-restoration complex during the mechanical fracture resistance test.[22] Another critical point to emphasize is that we measured dimensional and volumetric proportions and a low deviation was accepted when selecting samples. Teeth are biological structures with intrinsic morphological and compositional variability, which may influence the individual mechanical behavior of samples.[23,24,25] Operative dentistry procedures and dental material can also affect fracture resistance.[26] Thus, further studies should be conducted with homogeneous samples as resin teeth replicas with standard dimensions to remove the effect of this biological variable.

Conclusion

The following conclusions were drawn within the limitations of this *in vitro* study:

Crosshead speeds of 0.5–5.0 mm/min did not influence fracture resistance of restored maxillary premolars.

Crosshead speed of 10 mm/min decreased fracture resistance and also considerably modified the severity of the failure mode.

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