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Post-fatigue fracture resistance of premolar teeth restored with endocrowns: An *in vitro* investigation

Abstract

Objectives

To evaluate the post-fatigue load-to-failure and failure modes of endodontically treated premolar teeth restored with endocrowns fabricated from different CAD/CAM materials.

Materials and methods

A total of 60 extracted human, single-rooted premolar teeth were endodontically treated and sectioned horizontally 2 mm above the cementoenamel junction. Sectioned teeth were restored using two reconstruction designs: endocrowns (C_{endo}) or post-crowns (C_{post}) (n=30 p/g). In each group, reconstructions were fabricated from 3 different CAD/CAM substrates (n=10 p/g); a resin-based composite (Cera), a lithium disilicate glass ceramic (LiSi) and a monolithic, translucent zirconia (Zir). Additional 10 intact teeth were used as control. Restored teeth were subjected to dynamic fatigue test (10-50 N, 600,000 cycles) and thermocycling (5-55 °C, 1500 cycles). Load-to-failure and failure mode was determined following application of a static, 45° oblique compressive load on each specimen. One-way and Two-way analysis of variance (ANOVA), Tukey's *post hoc* and chi-square tests were used to determine statistically significant interactions among experimental and control groups.

Results

All specimens survived the mechanical and thermal fatigue tests. A statistically significant interaction between reconstruction design and material type was observed ($p<0.001$). C_{post}Zir and C_{endo}Cera groups exhibited significantly higher post-fatigue load-to-failure when compared to other materials of the same reconstruction design ($p \leq 0.001$). The highest frequency of catastrophic failures was observed with Zir reconstructions in both designs. Intact teeth exhibited significantly higher load-to-failure when compared to all groups ($p \leq 0.042$) except C_{post}Zir ($p=0.345$).

Conclusion

Single piece, CAD/CAM composite resin endocrowns can present a reliable option for restoring endodontically treated premolar teeth.

Clinical Significance

Endocrowns can be as effective as post-crowns provided appropriate preparation; material selection; and bonding protocols are utilized. Clinicians need to be cautious when prescribing zirconia endocrowns to restore premolar teeth owing to the low fracture resistance and high risk of catastrophic failures.

Keywords

Endodontic Treatment, Endocrowns, Post-Crowns, CAD/CAM, Zirconia, Lithium Disilicate, Resin Based Composite, Fracture Resistance.

1 Introduction

Endodontic therapy is a commonly prescribed treatment modality to treat pulpally involved teeth. More than often, endodontically treated teeth (ETT) are structurally compromised owing to the extensive tooth tissue loss [1]. Hence, the risk of biomechanical failures among ETT is rather high [2]. One key approach to minimize such failures is the preservation of remaining tooth structure and the provision cuspal coverage [2].

Full coverage crowns have been the first choice for restoring ETT [3]. They provide optimum cuspal protection however they require removal of significant amount of tooth structure [4]. Endodontic posts may be required to provide retention for a core that eventually retains a crown restoration [5]. Fibre-reinforced composite (FRC) posts are widely used in conjunction with composite resin core build up for rehabilitation of ETT. They confer a significant advantage as they provide immediate coronal seal following endodontic treatment and reduce the incidence of root fracture in comparison to cast metal counterparts [5]. Findings from *in vitro* and long-term clinical studies demonstrated high reliability and optimum performance of FRC posts [6, 7]. However, post space preparation may result in weakening of the radicular structure and subsequent root fracture. Periodontal trauma can occur as a result of iatrogenic root perforation or overheating during post space preparation [7]. Premolar teeth are more susceptible to the aforementioned complications given their thin tapered roots and associated developmental grooves [8].

Adhesive bonding of direct or indirect restorations may negate the need for using posts and thereby avoiding their adverse effects [9]. Adhesive restorations demonstrated adequate biomechanical performance *in vitro* and *in vivo* [10-12]. The type of the restorative material may affect the treatment outcome of weakened teeth owing to the inherent differences in elastic modulus [13]. Materials with relatively low elastic modulus, similar to dentin, may result in lower stress concentration and less catastrophic failures while high elastic modulus counterparts may exhibit higher fracture resistance [14].

Endocrowns are increasingly popular reconstruction choice to restore ETT [14-16]. The design of this monoblock reconstruction combines the features, and serves the function, of endodontic post, core and cuspal coverage coronal restoration [17, 18]. The cuspal coverage/protection is achieved by an occlusal onlay-like preparation. The retention of endocrown is obtained primarily from adhesive bonding [14, 15]. A central extension of the endocrown material into the endodontic access cavity increases the area available for bonding and thereby enhances retention [14, 15]. Additionally, the minimally invasive, defect-oriented preparation preserves enamel at the cavosurface margin which in turn, ensures a reliable adhesive bond [16]. A meta-analysis of 5 *in vitro* studies indicated superior fracture strength of endocrowns compared to conventional post-crown, inlay, onlay and direct composite resin restorations [16]. More recent systematic reviews indicated no difference between performance of post-crowns and endocrowns *in vitro* [19, 20]. Clinical data point toward optimum performance of endocrowns in general, with some concerns regarding their reliability to restore premolar teeth [19-21].

The widespread application of the computer assisted design/computer assisted manufacturing (CAD/CAM) has made chair-side fabrication of endocrowns feasible. Additionally, a multitude of materials can be readily utilized for this purpose including ceramic and resin-based composite (RC) materials [22].

The outstanding mechanical properties of zirconia dental ceramics resulted in extensive application of this material as a CAD/CAM substrate [23]. The dense crystalline structure and the unique phase transformation toughening are responsible for the high mechanical reliability of zirconia [24]. Further, the introduction of translucent zirconia enabled fabrication of minimally invasive and highly aesthetic, monolithic restorations [25]. Lithium disilicate (LD) glass ceramics are also reliable and highly aesthetic CAD/CAM substrates. Contrary to zirconia, they are susceptible to hydrofluoric acid etching and very reactive to silane coupling agent, hence the exceptionally reliable bond to tooth structure [26].

Post-milling sintering, a time-consuming process that may hinder the chair-side, single-visit restoration approach, is required with currently available LD glass ceramics and pre-sintered zirconia. It is required to initiate a solid-state reaction between the intermediate metasilicate phase and the surrounding glassy matrix to form the rod-like, interlocking LD phase crystals. Utilizing high density micronization (HDM) technology, a CAD/CAM glass ceramic substrate containing LD phase has been recently developed (Initial® LiSi: GC Dental, Europe) allowing milling of reconstructions that require no post-milling sintering.

CAD/CAM RCs are a group of materials with resin polymer matrices highly filled (>50% wt) with ceramic particles [27]. High temperature post-cure treatment is utilized to maximize the degree of conversion and to reduce polymerization shrinkage of CAD/CAM RCs, thus they require no post-milling sintering [27]. Such materials exhibit modulus of elasticity that is close to dentine resulting in lower brittleness compared to ceramics [28].

Maxillary premolars are the most commonly teeth involved in biomechanical failure as being subjected to high frequency/magnitude of non-axial loading during (para)function [29]. Further, multiple reports indicated suboptimal performance of endocrowns restoring premolars [19-21]. Then, it is prudent to assume that using low elastic modulus CAD/CAM RCs to fabricate endocrowns for premolar teeth may confer a biomechanical advantage. However, there is limited evidence regarding the effect of endocrown material on biomechanical performance. Additionally, the comparison between endocrown and a gold standard reconstruction, as post-crown, fabricated from CAD/CAM glass ceramic containing LD phase is yet to be reported. This *in vitro* investigation aimed to evaluate the influence of different restorative CAD/CAM substrates on the post-fatigue load-to-failure and failure modes of premolar teeth restored with endocrowns. The null hypotheses of this study are: (i) load-to-failure and failure modes of fatigued, restored ETT will be similar to control intact teeth, and (ii) reconstruction design and material type will have no effect on post-fatigue load-to-failure or failure mode.

2 Materials and methods

2.1 Selection of teeth, endodontic treatment and experimental groups

Seventy sound human mandibular and maxillary premolars extracted as part of orthodontic treatment plan were used in this study following ethical approval (Reference no. D/A 52). Periapical radiographs in bucco-lingual and mesio-distal directions were taken to ensure that all teeth had single root canal. Teeth were cleaned using an ultrasonic scaler and stored in 1% thymol solution prior preparation and testing. Ten intact premolar teeth were used as control.

Teeth in experimental groups were sectioned 2 mm above the cementoenamel junction (CEJ) using a water-cooled diamond cylindrical bur mounted on a high-speed handpiece. Teeth were endodontically instrumented using a combination of hand K-files and rotary instruments (Protaper® Universal; Dentsply Sirona, Switzerland). Root canal preparation was performed to F5 file and 1 mm short of apical foramina. A solution of sodium hypochlorite (2.5%) was used for irrigation between various files. Following mechanical preparation, sodium hypochlorite (2.5%), EDTA (5%) and distilled water were used for the final rinse. Next, root canals were dried with paper points and obturated using the lateral condensation technique, with gutta-percha (GP) and epoxy resin sealer (AH Plus® sealer; Dentsply Maillefer, Germany). GP cones were seared off at the CEJ point. Canal orifices were then filled with a provisional restorative material (Cavit™; 3M ESPE, USA). All treated teeth were incubated at 37°C and 100% humidity for at least 48 h to allow for complete set of the sealer.

The ETT (n=60) were randomly divided into two groups according to the reconstruction design; endocrowns (C_{endo}) or post-crown (C_{post}). Each group was further divided to 3 subgroups according to the reconstruction material (n=10 p/g) comprising of:

(i) Cera: CAD/CAM RC material, CERASMART®270 (GC Dental, Europe),
(ii) LiSi: LD glass ceramic material, Initial® LiSi blocks (GC Dental, Europe), and
(iii) Zir: Monolithic translucent zirconia material, Initial® Zirconia Disks HT (GC Dental, Europe).

2.2 Tooth preparation for endocrowns (C_{endo})

Tooth preparation was guided by recommendations of Pissis, 1995 [18]. A tapered, round-end, 80-µm grit diamond bur (SBR5 Smooth Cut; GC Dental, Europe) mounted on a high-speed handpiece was used to remove the temporary restoration and prepare a standardized 4 mm-deep, oval, central retention cavity extending in the pulp chamber. A resin-modified glass ionomer liner (Vitrebond®; 3M ESPE, USA) was applied over canal orifice and pulp chamber undercuts. The cavity base and inner surfaces were adjusted with the same diamond bur to obtain homogenous surfaces and to remove areas of stress concentration. All walls had minimum dentine thickness of 1 mm. Next, a 360° butt margin was prepared and smoothed. The preparation was then refined to eliminate undercut areas and achieve an unhindered path of insertion **(Fig.1)**. The amount of tooth tissue reduction was controlled using a periodontal probe.

2.3 Tooth preparation for post-crowns (C_{post})

Initial removal of the GP was accomplished using Gates Glidden drills (Dentsply Maillefer, Switzerland) retaining at least 3-5 mm of GP for apical seal. Post space preparation was refined utilizing the drill set provided in the RelyX™ Fibre Post kit (3M ESPE, St. Paul, MN). Glass FRC post (size 2) was placed in the canal, marked and cut at the point where it will be projected 3 mm in the composite resin core build up.

Sodium hypochlorite solution (5.25%) was used to clean root canal before cementation. The post space was rinsed with distilled water and then dried with paper points. Each post was cleaned with ethanol (77%), dried with air and then cemented using a dual-cured cement in conjunction with self-etching adhesive according to manufacturer's instructions (GRADIA™ CORE; GRADIA™ CORE Self-Etching Bond A & B; GC Dental, Europe). Then, a 3 mm-high core was built up with restorative composite resin (Herculite™ XRV; Kerr, Italy) using 1.5 mm increments and light cured for 40 s (Demi Plus; Kerr, USA). Fine diamond finishing burs were used to refine the core build up. Each tooth was prepared with a 2 mm-high, circumferential ferrule and a 1.0 mm-wide rounded shoulder margin at the CEJ.

2.3 Fabrication of coronal reconstructions

Prior to de-coronation, the coronal portion of each tooth was scanned using an intraoral scanner (CEREC Omnicam intraoral scanner; Dentsply Sirona). This scan was used to generate a biogeneric copy to fabricate a restoration replicating the original anatomy of the tooth using the CEREC 3D Software (Sirona, Bensheim, Germany).

The CEREC MCXL milling machine (Sirona, Bensheim, Germany) was used to mill Cera and LiSi restorations. Zir restorations were milled from pre-sintered zirconia disks using a 5-axes milling machine (Coritec 250i, imes-icore GmbH). The milled Zir restorations were sintered in a sintering furnace (LHT 01/17D; Nabertherm, Germany) according to the schedule specified by the manufacturer. Cera reconstructions were checked for fit and marginal adaptation then glazed (Optiglaze; GC Dental, Europe) according to manufacturers' instructions. LiSi and Zir reconstructions were polished using a sintered diamond rubber wheel (DiaFlex Fine; DiaShine®, USA).

2.4 Luting procedure

Fitting surfaces of LiSi reconstructions were etched using 9% hydrofluoric acid gel for 20 s while Cera and Zir reconstructions were sandblasted (50 µm Al_2O_3, 1.5 bar, 10 mm distance). A 1-Methacryloyloxydecyl Dihydrogen Phosphate (MDP) and silane containing ceramic primer was applied to the fitting surfaces of all reconstructions (G-multi primer; GC Dental, Europe). Light air flow was applied for 5 s to evaporate the ethanol solvent.

Enamel surfaces of prepared teeth were etched with 37% phosphoric acid gel for 30 s and dentine surfaces for 15 s, then rinsed and dried. The adhesive (G-Premio BOND; GC Dental, Europe) was applied using a microbrush, left for 10 s, air dried for 5 s, and then light cured for 10 s. Resin cement (G-CEM LinkForce; GC Dental, Europe) was loaded to the fitting surface of the reconstruction and seated on the prepared tooth with finger pressure. A 1 kg mass was applied to the seated reconstruction in a standardized procedure. Cement excess was removed with a microbrush and each surface was light cured for 40 s. Finally, reconstruction margins were polished using fine diamond points.

2.5 Dynamic fatigue test and thermocycling

Restored teeth were incubated at 37°C and 100% humidity for 48 h. Root surfaces were coated with glycerine and embedded in self-cured acrylic resin (Duralay; Reliance Dental Mfg, USA) up to 2 mm below the CEJ. Restored teeth were retrieved and re-embedded in the moulds with light consistency polyether impression material (Impregum™ Soft, 3M ESPE, USA) to simulate the presence of 0.2-0.4 mm-thick periodontal ligament (PDL) [30].

A dynamic fatigue testing machine (ElectroPuls E3000, Instron Corp., UK) was used to apply 600,000 loading cycles at a frequency of 5 Hz on all specimens. The effective load range exerted onto the specimens was 10-50 N at 45° angle to the long axis of the tooth. The load was applied using a 6 mm-diameter spherical tungsten carbide intender (KVJ A/S, Nykøbing F, Denmark). The test was performed whilst all specimens were immersed in 37℃ distilled water. Upon completion of the dynamic fatigue test, restored teeth were subjected to 1500 thermocycles (5°C and 55°C). Dwell time at each temperature was 30 s, and transfer time was 2 s.

2.6 Post-fatigue fracture resistance test

A universal testing machine was used to apply a static, compressive load on all specimens (Instron 3365, Instron Corp., UK). Load was applied at 45° angle to the long axis of the tooth with the aforementioned intender contacting the palatal plane of the buccal cusps at a crosshead speed of 0.5 mm/min until failure point. The load-to-failure was recorded using Instron Bluehill Software (Instron Corp., UK). Failure mode was examined for each specimen using an optical microscope (Olympus Optical CO. LTD, Tokyo, Japan) at *x*4 magnifications and categorized into one of the followings:

(i) Type 1: debonding of post, crown, or endocrown without fracture,

(ii) Type 2: fracture of the endocrown or post-crown but not tooth structure,

(iii) Type 3: fracture involving tooth structure above the level of CEJ, or

(iv) Type 4: fracture involving tooth structure at and below the level of CEJ.

Type 1, 2, and 3 failure modes were considered as retrievable failures while type 4 was considered as a catastrophic failure.

2.7 Statistical analysis

Shapiro-Wilk test indicated that load-to-failure data followed a normal distribution ($p>0.05$). Two-way ANOVA test was performed to examine main effects and 2-factor (reconstruction design and material type) interactions, multiple comparisons were performed using Tukey HSD post hoc test. Comparisons between experimental groups and control was performed using one-way ANOVA and Tukey HSD post hoc test. Chi-square test was used to compare C_{endo} and C_{post} in terms of failure modes regardless the reconstruction material. All analyses were performed using Statistical Package for Social Sciences software (Version 23, IBM® SPSS® Statistics, USA).

3 Results

All specimens survived the dynamic fatigue test and thermocycling without any detectable failure. Signs of contact wear were evident on the loaded area of all fatigued specimens. Two-way ANOVA demonstrated that the reconstruction design ($F=0.33$; $p=0.569$) and material type ($F=2.75$; $p=0.071$) had no significant effect on the load-to failure variable, but the interaction effect was statistically significant ($F=26.83$, $p<0.001$). C_{endo}Cera exhibited a significantly higher load-to-failure compared to C_{endo}LiSi/Zir groups ($p\leq0.001$) but no statistically significant difference was observed between the latter groups ($p=0.162$). C_{post}Zir exhibited significantly higher load-to-failure compared to C_{post}LiSi/Cera groups ($p<0.001$).

No significant difference between C_{post}LiSi and C_{post}Cera was detected ($p=0.358$). The control group of intact teeth demonstrated significantly higher mean post-fatigue load-to-failure when compared with all other experimental groups ($p\leq0.042$) except for C_{post}Zir ($p=0.345$).

Failures in Zir reconstructions were primarily catastrophic ($p=0.011$). No single characteristic failure mode could be determined for the other experimental groups (40-60% catastrophic failures). Comparing the failure modes between the two reconstruction designs regardless the material type, no significant difference was observed ($p=0.573$). In cases of root fracture, it was observed that fractures occurred in a mesio-distal direction around the mid sagittal axis in the direction of the applied static load. Only one specimen in C_{endo}Zir group sustained a horizontal root fracture at the level of endocrown pulpal extension. Crown de-bonding was observed once in C_{post}LiSi group (type 1 failure) **(Fig 2)**. The mean (SD) of post-fatigue load-to-failure values and failure modes of all experimental groups are presented in **Table 1**.

4 Discussion

The purpose of this *in vitro* study was to investigate the load-to-failure and failure modes of endodontically treated premolars restored with endocrowns or post-crowns fabricated from three contemporary CAD/CAM materials. Intact premolar teeth with comparable root diameter, at the CEJ, and root length were chosen (±10% of mean value). The use of natural teeth for testing might be a source of variability, though it accurately represents the *in vivo* situation. The use of un-fatigued, sound teeth as control provides a reliable indicator on structural integrity and strength of the used reconstruction design and material. Control teeth demonstrated significantly higher load-to-failure compared to all experimental groups ($p \leq 0.042$) except zirconia post-crowns ($p=0.345$), leading to partial rejection of the first null hypothesis. Our findings agree with another study where both LD glass ceramic endocrowns and post-crowns exhibited significantly lower post-fatigue load-to-failure in comparison to intact teeth [31]. The high load-to-failure of zirconia post-crowns in this study can be attributed to the exceptional strength of zirconia, the high tenacity of the glass FRC post and optimum adhesive bonding protocol [32]. Additionally, the presence of circumferential 2-mm ferrule combined with glass FRC resulted in reduced stress concentration in the cervical area and allowed better force distribution along the radicular remaining tooth structure [32].

Single operator performed all experimental work in order to ensure standardized specimen preparation and testing. Fabrication of all reconstructions using a biogeneric copy may allow extrapolation of clinically relevant findings. Application of 600,000 loading cycles mimics 2.5 years of *in vivo* function [33]. Performing the test in distilled water accounts for the possibility of water-assisted sub-critical crack growth [34]. The latter process is known for its' deleterious effects on the reliability of ceramic materials. Light body polyether impression material was used to simulate PDL in this study which reportedly influenced load-to-failure and failure pattern in fracture resistance tests [35]. This material was particularly chosen as it exhibits a non-linear behaviour when subjected to external stress and elastic modulus similar to PDL [36]. Application of dynamic and static load at 45° resembles accentuated non-axial loading, replicating worst possible scenario where force is concentrated on the cervical area. All CAD/CAM substrates used in this study were produced by one manufacturer which can potentially limit the generalisability of the findings of this study. Nonetheless, *in vitro* and *in vivo* research studies demonstrated comparable properties/performance of the used materials when compared to counterparts produced by other manufacturers [37].

In this study, all tested specimens survived the dynamic fatigue and thermocycling. This is an important finding as de-bonding was the primary cause of premolar endocrowns failure in a 5-year clinical study [17]. The high biomechanical reliability of the coronal reconstructions and durable resin adhesive bond may be responsible for the optimum fatigue resistance. Additionally, the adequate tooth structure and restoration preparation/priming, and the use of

MDP-based resin cement can also explain the low number (n=1/60) of de-bonded restorations during post-fatigue fracture resistance test [38, 39].

The higher estimates of bite force in the premolar region were reportedly 520 N during function and 800 N during clinching [40, 41]. It is rational to expect a notable increase in such values in ETT owing to the lack of tactile sensory mechanism of the dental pulp [42]. In the current study, only CAD/CAM RC endocrowns and zirconia post-crowns exhibited mean load-to-failure exceeding 750 N indicating adequate biomechanical reliability during (para)functional activities. Both groups exhibited significantly higher load-to-failure compared to other materials in their respective reconstruction design groups ($p \leq 0.001$) leading to partial rejection of the second null hypothesis. However, when the reconstruction design and type of material independent variables were evaluated individually, both had no significant effect on load-to-failure values ($p=0.569$, $p=0.071$, respectively). Interaction effect of reconstruction design and material type was found statistically significant ($p<0.001$).

A finite element analysis study demonstrated concentration of stresses at the endocrown-tooth structure interface [43]. Further, it has been reported that significant mismatch of elastic moduli between tooth structure, reconstruction material and intervening cement layer may predispose for catastrophic failures involving root surface [43]. This effect was evident in both reconstruction designs as the highest percentage of catastrophic failures was observed with zirconia reconstructions ($p=0.011$). The application of an oblique load on stiff zirconia resulted in stress concentration on the facial-cervical area of the root resulting in spall formation involving the CEJ and beyond.

Utilizing restoratives with lower elastic modulus may, in theory, improve the biomechanical behaviour of the restorative system. CAD/CAM RCs are composed of polymer-matrices containing predominantly ceramic fillers and exhibit elastic modulus lower than ceramic materials [27]. Such materials have a higher tendency to bend under loading and distribute stresses more evenly leading to lower catastrophic failures [28]. *In vitro* studies demonstrated higher fracture strength and fewer catastrophic failures of CAD/CAM RC endocrowns restoring premolars when compared to LD glass ceramic counterparts [44, 45]. However, one major concern is the de-bonding of such restorations as a result of stress concentration at the adhesive interface during function.

The CAD/CAM RC (Cera) material used in this study contains glass-based materials as inorganic filler (71% wt: Barium borosilicate glass and silica) in organic resin matrix [27]. It exhibits elastic modulus comparable to dentine (E=9.25 GPa) [46]. None of Cera reconstructions, endocrowns or post-crowns de-bonded during dynamic fatigue, thermocycling or fracture strength test, dismissing concerns regarding high risk of adhesive bond failure. Further, C_{endo}Cera demonstrated significantly higher load-to-failure as an endocrown material when compared to LD glass ceramic and zirconia ($p \leq 0.001$). The lowest number of catastrophic failures was also observed in Cera reconstructions. Further, C_{post}Cera demonstrated significantly lower load-to-failure compared C_{post}Zr group ($p<0.001$). This can be attributed to the difference in strength of Zir and Cera at 1 mm axial thickness [32, 47]. In C_{post}Cera group, all failures initiated at the cervical-facial aspect of the crown contrary to C_{post}Zr where this area was intact in most fractured specimens. In C_{endo}Cera, the endocrown margin is placed more coronal and the oblique static loading is primarily resisted by natural tooth structure, thus demonstrating higher load-to-failure.

In general, CAD/CAM RCs have improved physical properties, wear resistance and colour stability when compared with direct resin composites owing to the high degree of conversion achieved via post-cure, heat and/or pressure polymerisation [47, 48]. Further, CAD/CAM RCs may outperform ceramic counterparts for the following reasons: (i) reduced time, cost and flaws associated with milling process, (ii) no post-milling sintering is required, (iii) ease of adjustment, finishing and polishing with no need to glaze, (iv) less antagonistic tooth wear, and (v) improved repairability and modification using direct composite resin [47, 48]. However, CAD/CAM RCs exhibit lower wear resistance, inferior aesthetic properties, higher water sorption and plaque retention when compared to ceramics [48].

One concern with CAD/CAM RC materials is their high coefficient of thermal expansion. Thermocycling of endocrowns fabricated from a CAD/CAM RC substrate (Lava™ Ultimate, 3M ESPE, USA), resulted in significantly higher microleakage in comparison to feldspathic and LD glass ceramic endocrowns [44]. Coefficient of thermal expansion is largely affected by the resin content, since resins are the expansile phase of the material. Thus, we expect that microleakage can be more significant with Cera as the resin matrix constitutes 29% wt of the material compared to 20% wt of the Lava™ Ultimate [27]. Further *in vitro* and clinical studies are required to elucidate the effects of water storage and thermocycling on the marginal fit of endocrowns fabricated from various types of CAD/CAM RCs.

No significant difference was observed between LiSi endocrowns and post-crowns in terms of load-to-failure and failure modes ($p>0.573$) which was in agreement with previous studies used conventional LD glass ceramics [31, 49]. However, other studies reported superior reliability of LD glass ceramic endocrowns compared to post-crowns [14, 50]. Different testing methods and parameters may explain such contradicting findings. Further, the LD glass ceramic used in this study may differ significantly from previously investigated materials. In the current study, a newly developed LD phase containing glass ceramic was used. The ease of milling is the hallmark of this advent owing to the homogenous dispersion of LD micro-crystals within the glassy matrix. This material requires no post-milling sintering and thereby may result in better marginal adaptation via elimination of margin distortion observed with post-milling sintering [51]. As per the manufacturer, the milled substrate exhibits very smooth surface finish and requires simple polishing which we did not investigate but we have observed in this study.

Despite the high compatibility between elastic moduli of Cera and dentine, 40% of C_{endo}Cera specimens sustained catastrophic failures. This can be related to the high load-to-failure, which allowed for greater transmission of force to the tooth structure. A similar effect was observed in another study as it has been reported that high fracture strength was associated with catastrophic fracture patterns regardless of the reconstruction design or material [52]. Further, endocrown margins were placed too close to CEJ, contrary to most clinical situations, which can explain the relatively high number of catastrophic failures. No statistically significant difference could be observed between in failure modes among the different reconstruction designs regardless the reconstruction material ($p=0.573$), leading to partial acceptance of the second null hypothesis.

From a clinical point of view, endocrowns are less time-consuming, cost-effective, contain a single adhesive interface and are associated with minimal risk of iatrogenic damage or technical complications [17, 53]. The supragingival butt margins required for endocrown preparation are easy to prepare and record with conventional or optical impressions. Assessment of the marginal fit, cement excess removal and maintenance of endocrowns are simpler compared to post-crown reconstructions. Recording the details of the apical part of retention cavity can be concerning with intraoral scanners. However, endocrowns with pulpal extension of 2.5 mm or 5 mm could withstand occlusal forces in the premolar region [52]. Thus, clinicians can prepare shallower retention cavities to avoid such problems. Additionally, the depth scale can be as high as 6.4 mm in some intraoral scanner [54].

Loss of retention can be a major concern for endocrowns restoring premolar teeth. This can be related to the small surface area available for bonding as well as limited penetration ability of the curing light to polymerise resin cement in the retention cavity. However, the lack of premature failures or de-bonded reconstructions during dynamic fatigue and fracture resistance tests indicating optimum retention of the investigated endocrowns. The current investigation demonstrated that endocrowns may perform as well as post-crowns to restore endodontically treated premolar teeth. Though long-term clinical studies are required to substantiate these *in vitro* findings.

5 Conclusions

Within the limitations of the present *in vitro* investigation, the following conclusions can be made:

(i) Post-crown and endocrown reconstructions restoring endodontically treated premolar teeth survived dynamic fatigue test and thermocycling.

(ii) The investigated CAD/CAM resin-based composite material and monolithic translucent zirconia resulted in highest load-to-failure among endocrown and post-crown reconstructions, respectively.

(iii) Monolithic translucent zirconia resulted in the highest number of catastrophic failures in both reconstruction designs.

(iv) The investigated lithium disilicate glass ceramic CAD/CAM material demonstrated comparable load-to-failure and similar number of catastrophic failures in both reconstruction designs.

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