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ORIGINAL ARTICLE

Fracture load of three-unit full-contour fixed dental prostheses fabricated with subtractive and additive CAD/CAM technology

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Abstract

Objectives The aim of this study was to test the fracture load of ceramic and composite three-unit full-contour fixed dental prostheses (FDPs) fabricated with additive and subtractive computer-aided design (CAD)/computer-aided manufacturing (CAM) technology.

Materials and methods A newly developed alveolar socket replica model for a three-unit FDP replacing one molar was used in this study. Five CAD/CAM materials were used for fabrication of three-unit FDPs (each $n = 12$). The subtractive CAD/CAM fabrication method was used for groups BC (BRILLIANT Crios), TC (Telio CAD), EX (e.max CAD), and TZ (inCoris TZI C), and the additive method was used for group 3D (els 3D resin even stronger). FDPs were adhesively seated to the abutment dies (PANAVIA V5 system). Thermomechanical loading was performed prior to fracture testing with a universal testing machine. The data for maximum fracture load values was analyzed with one-way ANOVA and post hoc Scheffé test ($\alpha = 0.05$).

Results All FDPs survived the thermomechanical loading test. Statistically significant differences were found for the fracture load of three-unit FDPs fabricated from different CAD/CAM materials ($p < 0.05$). The highest mean fracture load was found for group TZ (2099.5 ± 382.1 N). Group 3D showed the lowest mean fracture load (928.9 ± 193.8 N). Group BC performed statistically significantly differently from group 3D with a mean fracture load of 1494.8 ± 214.5 N ($p < 0.05$).

Conclusions Particle-filled composite resin CAD/CAM materials showed fracture load values within the range of ceramic materials with a specific indication of use for three-unit FDPs.

Clinical relevance Particle filled composite CAD/CAM materials may offer new treatment possibilities for the CAD/CAM workflow.

Keywords CAD/CAM · Composite · Ceramic · Three-unit FDP · CEREC

Introduction

Three-unit fixed dental prostheses (FDPs) are a viable prosthetic treatment option for the replacement of missing teeth and an alternative to single-implant restorations if proper indication is provided [1, 2]. Different material options are available for the fabrication of three-unit FDPs. In the past, full-metal or metal frameworks veneered with ceramic have been used for FDPs whereas metal-based FDPs have often been associated with esthetic shortcomings. Metal-free monolithic and veneered all-ceramic systems have thus become increasingly popular for the fabrication of FDPs in recent times [3].

Several different material options for FDPs have been analyzed using different in vivo test setups, and survival rates up to 93% after 8 years for three-unit lithium silicate glass-ceramic FDPs have been reported [4–10]. The phenomenon of chipping of veneering ceramic and fractures within the connector dimension are among the most commonly described failures for all ceramic FDPs [11]. Recent developments in material science thus aim to strengthen the structure of the ceramic framework and refrain from the veneering process for FDPs. High-strength zirconia-based monolithic ceramic materials with improved esthetic characteristics have thus become increasingly popular for the use of multi-unit permanent FDPs [12].

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Both ceramic and composite resin materials are used for the fabrication of indirect computer-aided design (CAD)/computer-aided manufacturing (CAM) restorations. Despite their inferior esthetic characteristics, CAD/CAM composite materials have become increasingly popular for the use of single-unit restorations [13]. Intraoral repairability, easy postprocessing, and high margin stability during CAM fabrication have been described as the main advantages of CAD/CAM composite materials [14–16]. Up to now, CAD/CAM composite materials are mostly available for subtractive fabrication procedures in the form of CAD/CAM composite blanks or blocks [17]. New approaches in terms of additively fabricated permanent CAD/CAM composite materials using 3D printing technology have been recently described [18]. In contrast to subtractive CAD/CAM fabrication with a high amount of material loss and susceptibility for instrument wear, additive fabrication builds up the object layer by layer with less restriction for 3D geometrical shaping.

The different CAD/CAM material options that are available for multi-unit FDPs comprise permanent and non-permanent restorations with very specific indications such as the number of abutment and pontics. CAD/CAM polymers and fiber-reinforced PMMA-based composites only cover the indication of temporary FDPs [19–22]. The indication for CAD/CAM composite materials is limited to permanent single-tooth restorations [13]. There might be thus the question if resilient CAD/CAM restoration materials might be a suitable alternative for the indication of use for multi-unit FDPs. In literature, a low E-modulus of the FDP framework material has been demonstrated to result in a more even stress distribution within the framework [23, 24]. This finding might be considered when evaluating the catastrophic load to fracture testing of FDPs which is normally performed to evaluate the clinical performance with specific in vitro test setups. Up to now, there is no study evaluating the fracture load of CAD/CAM composite materials for multi-unit FDPs.

The aim of this study was to test the fracture load of ceramic and composite three-unit full-contour fixed dental prostheses (FDPs) fabricated with additive and subtractive CAD/CAM technology. The null hypothesis of this study was that there are no statistically significant differences for the fracture load of CAD/CAM-fabricated three-unit FDPs made from different CAD/CAM materials.

Materials and methods

This study comprised thermomechanical loading and the subsequent fracture loading of adhesively seated three-unit FDPs made from different CAD/CAM materials on a newly developed in vivo–like alveolar socket replica model. The setup model was a simulation of a three-unit FDP comprising the replacement of one posterior molar (tooth 35–tooth 37). The setup model parameters were as follows: abutment central distance 20 mm, preparation margin: deep chamfer 0.8 mm; abutment height 5.4 mm; and alveolar socket depth 10.8 mm. BRILLIANT Crios CAD/CAM composite resin material (Coltène AG; Altstätten, Switzerland) with dentin-like E-modulus (10 GPa) was used as abutment die material. BreCAM.bioHPP polyetheretherketone (PEEK) material (bredent medical GmbH; Senden, Germany) with alveolar bone–like E-modulus (4 GPa) was used as artificial bone material, including sockets. The design of both components was manually done with 3D Builder CAD design software (v.16.1.741.0; Microsoft; Redmond, WA, USA). The fabrication of both components was conducted using the subtractive CAD/CAM technology (MCX5 milling unit; Dentsply Sirona; York, PA, USA). The simulation of the periodontal ligament was achieved with the polyvinylsiloxane material PRESIDENT light body (Coltène AG). The spacer for the periodontal ligament was approximately 100 μm. The axial wall taper for both abutment dies was 6°. Figure 1 illustrates the respective setup model used in this study.

The design and fabrication of FDPs were done using the CAD/CAM workflow. The setup model, including abutment, was digitized with the dental lab scanner inEOS X5 (Dentsply Sirona). The CAD design of the master full-contour three-unit FDP was performed with the dental CAD software inLab 16 (v.16.0.0.64055; Dentsply Sirona). The CAD design parameters for the three-unit FDPs were as follows: connector size 16 mm^2; anatomic-ovoid-shaped connector design; minimum occlusal thickness 1.5 mm; and replacement of one molar. The material thickness and CAD design were identical for all groups. The master design file was exported into STL file format and forwarded to the different production methods.

The overview for the CAD/CAM materials used in this study is shown in Table 1. Five CAD/CAM materials were used for the fabrication of the three-unit FDPs: BC (BRILLIANT Crios; Coltène AG), 3D (els 3D resin even stronger; Saremco Dental AG; Rebstein, Switzerland), TC (Telio CAD; Ivoclar Vivadent AG; Schaan, Liechtenstein), EX (e.max CAD; Ivoclar Vivadent AG), and TZ (inCoris TZI C; Dentsply Sirona). Manufacturers' recommendation for indications of use for the respective CAD/CAM materials is up to a permanent four-unit FDP for group TZ, up to a permanent three-unit FDP up to the second bicuspid as distal abutment for group EX, and up to a four-unit temporary FDP for group TC. Indications of use for groups BC and 3D are limited to permanent single-tooth restorations.

The subtractive CAD/CAM fabrication method with the MCX5 milling unit using inLab CAM software (v.16.0.0.66246; Dentsply Sirona) was used for group BC, and with the inLab MCXL milling unit (Dentsply Sirona) for groups TC, EX, and TZ. CAM strategies optimizing the material characteristics were used and were comprised of dry milling (BC, TZ), wet milling (TC), and wet grinding (EX).

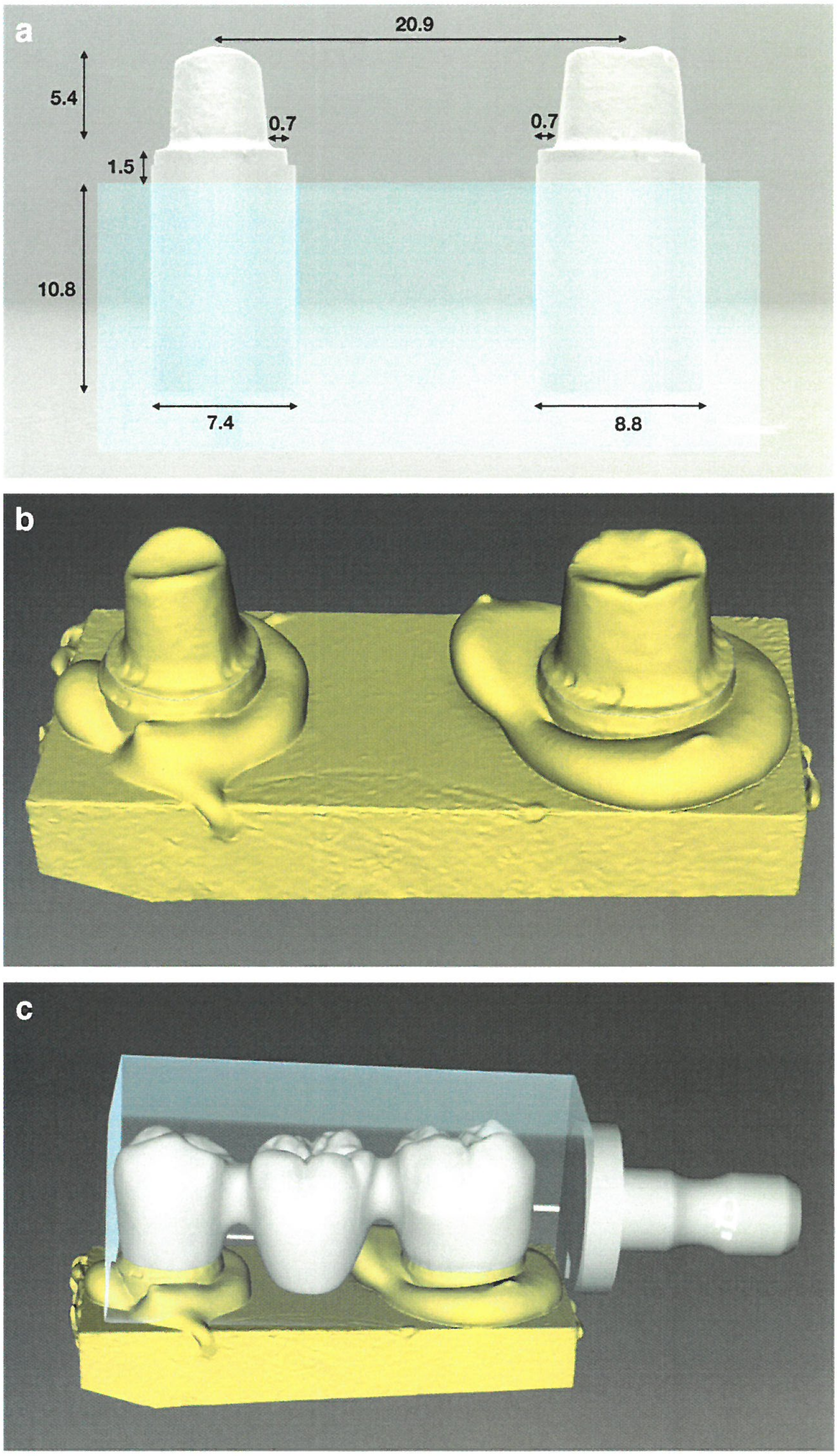

Fig. 1 **a** CAD design three-unit FDP setup model with respective parameters (in mm); simulation of periodontal ligament thickness of 100 μm. **b** Alveolar socket replica model for three-unit FDP digitized with inEOS X5. **c** Three-unit FDP designed with CAD software inLab 16 (example shown for group EX)

Restorations were fabricated from 98.5 mm diameter CAD/CAM blanks (BC), CEREC block medi S (TZ), CEREC block B32 (EX), and CEREC block B40L (TC). Postprocessing protocols were performed according to the manufacturers' recommendations for FDPs using the crystallization firing process (Programat CS; Ivoclar Vivadent AG, Schaan, Liechtenstein) for group EX and the sintering firing process (inFire HTC; Dentsply Sirona; York, PA, USA) for group TZ. Ceramic-based specimens were not glazed and resin-based specimens were not polished after CAM fabrication. The additive CAD/CAM fabrication method with the Asiga Freeform PRO2 DLP printer (ASIGA; Anaheim Hills, CA, USA) was used for group 3D. Parameters were set to slice thickness at 50 μm, exposure time at 1 s, minimum/maximum light intensity at 18.34 mW/cm^2, z compensation at 0 μm, and xy compensation at 0 μm. Postprocessing

Table 1 Overview groups and material characteristics used for fabrication of three-unit FDPs; *values for E-moduli and flexural strength were taken from manufacturers' safety sheet data; fabrication method: *DM* dry milling, *3D* 3D printing, *WM* wet milling, *WG* wet grinding

Group	Material label (LOT)	Composition	E-modulus*	Flexural strength*	Fabrication
BC	BRILLIANT Crios (20180626CDR)	Organic matrix: cross-linked methacrylates; anorganic fillers: barium glass and silicon dioxide (70.7%w-%)	10.3 GPa	198 MPa	DM
3D	els 3D resin even stronger (170918-01)	Organic matrix: methacrylate monomers; anorganic fillers: dental glass silica	4.5 GPa	152 MPa	3D
TC	Telio CAD (WY1739)	Organic matrix: polymethylmethacrylate	3.2 GPa	130 MPa	WM
EX	e.max CAD (X11930)	Ceramic glass phase with embedded crystallites: Li_2SiO_5 (70%)	90 GPa	500 MPa	WG
TZ	inCoris TZI C (2016088609)	Oxide ceramic $ZrO_2 + HfO_2 + Y_2O_3$ (≥ 99.0%), Y_2O_3 (> 4.5–≤ 6.0%), HfO_2 ≤ 5%, Al_2O_3 (≤ 0.04%), other oxides (1.1%)	210 GPa	> 900 MPa	DM

protocol for FDPs of group 3D comprised cleaning and washing in isopropanol for 2 × 5 min using ultrasonic cleaner with a subsequent light curing with 4000 lighting exposure using a Xenon lamp curing device with a N_2-gas atmosphere (Otoflash G171; NK Optik, Baierbrunn, Germany) (2 flashlight lamps, wavelength range 280–580 nm, peaks at approximately 480 and 530 nm). For each group, twelve specimens were fabricated ($n = 12$; 5 groups).

The FDPs were adhesively seated to abutment dies in respect to a total adhesive luting protocol using the PANAVIA V5 system according to the manufacturers' recommendations (abutment die: sandblasting with 50 μm aluminum oxide, application of PANAVIA V5 tooth primer for 10 s; restorations: application of Ceramic Primer Plus for at least 60 s). The intaglio surfaces of FDPs were pretreated according to the manufacturers' recommendations prior to adhesive bonding, using either sandblasting with 50 μm aluminum oxide and ultrasonic cleaning (BC, 3D, TC, TZ) or 5% hydrofluoric acid etching for 20 s (EX).

Thermomechanical loading was performed in respect to a standardized protocol in a chewing simulator (1.2 mio cycles, frequency 1.7 Hz, invariable occlusal load 49 ± 0.7 N, dwell time 120 s, water change time 10 s, 5/55 °C) [25]. Cusps of a natural tooth molar were used as an antagonist with loading exactly in the central fossa of the pontic tooth element. After thermomechanical loading, examination of FDPs in regard to fractures or cracks was carried out with a stereomicroscope at × 14 magnification and transmitted light (Wild Leitz/M1B, Walter Products; Windsor, ON, Canada). Only intact FDPs were forwarded to subsequent fracture loading.

Fracture loading was performed with the Allround Line z010 universal testing machine (Zwick; Ulm, Germany) using a standardized protocol (crosshead speed 1 mm/min, ball diameter 5 mm). Maximum loading force was applied to the central fossa of the pontic tooth element until catastrophic fracture. Fracture load values were automatically registered in Newton (N).

All data was forwarded to the SPSS Statistics analysis program (v.25; IBM, Armonk, NY, USA). Data was tested for normal distribution using the Shapiro-Wilk test and for homogeneity of variances using Levène test. One-way ANOVA and post hoc Scheffé test were used for statistical analysis (significance level $\alpha = 0.05$).

Results

All FDPs survived the thermomechanical loading test and were forwarded to fracture load testing. The overview about mean fracture load values for test groups is shown in Table 2. The data for fracture load was normally distributed (the Shapiro-Wilk test, $p > 0.05$) with homogeneity of variances (Levène test, $p > 0.05$). The one-way ANOVA test revealed mean fracture load values to be statistically significantly different ($p < 0.05$). The highest fracture load values (mean ± standard deviation) were found for group TZ (2099.5 ± 382.1 N). Group 3D showed the lowest mean fracture load (928.9 ± 193.8 N) and performed statistically significantly differently from the subtractive CAD/CAM composite material BC (1494.8 ± 214.5 N). The CAD/CAM composite material BC performed statistically significantly differently from the ceramic CAD/CAM material EX (1094.6 ± 149.7 N). The overview of statistical results for fracture load values is shown in Table 3.

Table 2 Maximum fracture load [N] for three-unit FDPs in the different experimental groups; *n* number of specimens

	n	Mean	SD	Min	Max	95% confidence interval	
						Lower	Upper
BC	12	1494.8	214.5	1075.4	1808.9	1358.5	1631.0
3D	12	928.9	193.8	586.9	1172.6	805.8	1052.1
TC	12	1221.3	198.5	792.2	1453.3	1095.2	1347.4
EX	12	1094.6	149.7	789.4	1273.7	999.5	1189.7
TZ	12	2099.5	382.1	1632.1	3017.8	1856.7	2342.3

Discussion

In this study, the fracture load of CAD/CAM-fabricated and 3D-printed composite full-contour three-unit FDPs was investigated using a newly developed alveolar socket replica model fabricated with CAD/CAM technology. Five CAD/CAM materials were used for the fabrication of three-unit FDPs. Ceramic-based CAD/CAM materials were chosen as typical representatives for high-strength (TZ) and low-strength (EX) materials covering permanent FDP indication. The main objective of this study was to evaluate the fracture load of CAD/CAM composite materials compared with CAD/CAM materials already comprising the three-unit FDP indication. Based on the results found in this study, the null hypothesis that there are no statistically significant differences for the fracture load of CAD/CAM-fabricated three-unit FDPs made from different CAD/CAM materials has to be rejected.

Occlusal loading forces occurring during mastication vary individually and have been reported to be highest in the posterior area for adult men with approximately 600 N [26, 27]. Fracture loading results found in this study were promising for all CAD/CAM materials tested with values higher than 600 N for all test groups.

In this study, thermomechanical loading was performed prior to fracture load testing using a standardized protocol. The influence of thermomechanical loading on fracture load values has been discussed critically in recent literature [28]. The effect of aging on CAD/CAM materials might predominantly depend on specific material characteristics. Beuer et al. demonstrated that thermomechanical aging did not have a significant effect on the fracture load of zirconia-based three-unit FDPs [12]. Stawarcyzk et al. demonstrated that the fracture load of polymer-based CAD/CAM composite resins was not affected by thermomechanical loading [29]. Up to now, there are no studies evaluating the effect of thermomechanical loading on FDPs fabricated from CAD/CAM composite materials. Mechanical and chemical degradations for CAD/CAM composite materials have recently been analyzed, revealing a higher water uptake and a higher thermal expansion compared with ceramic CAD/CAM materials [30].

Table 3 Homogenous subset groups as a result of statistical analysis of maximum fractural load values with one-way ANOVA and post hoc Scheffé test; significance level $\alpha = 0.05$; values within one subset group show no statistically significant difference ($p > 0.05$)

Fracture load			
Material group	Subsets for alpha = 0.05		
	1	2	3
3D	928.9		
EX	1094.6		
TC	1221.3	1221.3	
BC		1494.8	
TZ			2099.5
Sig.	0.081	0.119	1.000

In this study, fracture loading was performed using a standardized protocol. Parameters for fracture loading were within the range of similar studies with a crosshead speed of 1 mm/min and a ball diameter size of 5 mm [28]. In this study, fractures for FDPs always occurred within the connector element starting at the gingival interdental embrasure. This observation is in good accordance with the findings of recent literature. Both in vitro and finite element studies revealed that cracks and fractures for FDPs initiate from the gingival surface of the connector as the tensile loading weak point toward the pontic [31, 32].

In this study, the highest mean fracture load for three-unit FDPs was found for group TZ with 2099.5 ± 382.1 N and the lowest fracture load was found for group 3D with 928.9 ± 193.8 N. Several studies have been published evaluating the in vitro fracture load of three-unit FDPs for CAD/CAM polymer–based composite resin and CAD/CAM ceramic–based materials [29, 33, 34]. Results of this study are in good accordance with these findings.

Many setup parameters influence the results of fracture load such as the test material, test setup characteristics such as abutment die material and alveolar socket material, and parameters for fatigue loading and fracture loading [25, 28, 35–37]. These variables make it difficult to draw direct conclusions from previous study results to values for identical CAD/CAM materials evaluated in this study. Several different test setup models have been used for the evaluation of the fracture load of three-unit FDPs, with most studies using a stainless-steel setup model [28]. The E-modulus of the abutment die material and the simulation of the periodontal ligament have been demonstrated to have a significant effect on the fracture load of FDPs [37, 38]. Studies have shown that the fracture strength of FDPs mainly depends on the stability of the abutment to reduce strain in the beam of the prosthesis [39]. Wimmer et al. demonstrated that higher fracture load values are found for three-unit FDPs made from CAD/CAM materials with a high E-modulus if stiff abutment die materials are used, whereas CAD/CAM materials with a low E-modulus had higher fracture values if more resilient abutment die materials were used [37].

In this study, an existing test setup model was adapted to simulate material properties of the supporting structures of the abutment die and the surrounding alveolar bone [29]. Alveolar sockets were fabricated from PEEK material breCAM.bioHPP (E-modulus 4 GPa), and abutment dies were fabricated from CAD/CAM composite material BRILLIANT Crios (E-modulus 10 GPa). The reason for the selection of both materials was the similarity of their E-modulus with actual in vivo conditions. The E-modulus of dentin is reported to range between 7 and 13 GPa [40]. Values for the E-modulus of alveolar bone vary widely depending on the respective location and have been reported to be between 0.2 and 9.6 GPa [41]. The imitation of in vivo–like conditions with a match of different E-moduli of the respective components of the setup model is a trait particular to this study. Most setup models for fracture load testing do not simulate artificial periodontium, although simulation of resilient periodontal ligament has been demonstrated to reduce the fracture resistance of FDPs [3]. In this study, the simulation of the periodontal ligament was done with PRESIDENT light body polyvinylsiloxane material. However, every in vitro model only approximates one specific intraoral restorative situation. The broad variety of clinical factors possibly influencing the fracture load of restorations (e.g., root morphology) cannot be fully simulated in one in vitro model. The advantage of an in vitro test setup is basically a highly standardized reproducibility of the mechanical characteristics of the test model itself. Preparation design of abutment dies thus had to be identical for all tested material groups despite the manufacturers' specific recommendations for the respective material groups.

The quality of adhesive bonding might influence the values found for fracture load testing since debonding events might result in a premature fracture of the restoration. Adhesive bonding has been shown to increase fracture load values for single-unit FDPs [42]. Wimmer et al. showed an influence of cementation on stress distribution of FDPs in an FEA analysis setup for three-unit FDPs [43]. Studies show that a high bond strength on the composite material used for the abutment dies is possible with a proper adhesive pretreatment protocol [44]. The observed fracture patterns showed that all FDPs failed due to fractures in connector areas with no debonding on the abutment dies. No debonding on the abutment dies was observed neither after thermomechanical loading nor after fracture load testing.

Results of this study show that fracture load values for particle-filled composite resin CAD/CAM materials are within the range of ceramic CAD/CAM materials with specific indication of use for three-unit FDPs. Resilient CAD/CAM materials have the capability to dissipate destructive fracture energy by elastic and plastic deformation to a greater extent than stiffer ceramic CAD/CAM materials because of their lower E-modulus. Filler particles stop the crack propagation via crack deflection and bridging effects and thus increase the flexural strength of restorative materials. In this study, composite materials with a high amount of filler particles (BC) show higher fracture load values compared with composite material with lower amount of filler particles (3D). Unfilled PMMA materials (TC) exhibit high fracture load values as well based on the very low E-modulus resulting in a high elastic deformation. On the one hand, the resilient material characteristics might thus be beneficial for FDPs made from composite materials with fracture load values similar (3D, TC) or higher (BC) than lithium disilicate glass ceramics (EX) whereby it has to be remembered that recent studies have demonstrated that resilient framework materials for FDPs do not negatively influence the biomechanical loading of the involved biological structures [24]. On the other hand, factors like high wear resistance and color stability are important for permanent restorations [45]. This is one reason why the unfilled PMMA material is only indicated for temporary restorations. For ceramic materials, highest fracture load values were found for zirconium oxide ceramic. This is a common finding in other studies, based on the crystalline structure of this material [12, 35, 38]. Additionally, parameters like abrasion and color stability are superior for ceramic materials compared with those for composite materials.

Conclusion

Particle-filled composite resin CAD/CAM materials show fracture load values within the range of ceramic materials with specific indication of use for three-unit FDPs. Based on the fracture load values and despite the previously mentioned shortcomings of composite materials, particle filled CAD/CAM composites might be a viable material option for the fabrication of FDPs.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

Disclaimer Both companies had no influence in the study design, nor in the collection, analysis, or interpretation of the data, nor in writing or submitting the publication.

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