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Simulated Cuspal Deflection and Flexural Properties of Bulk-Fill and Conventional Flowable Resin Composites

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Clinical Relevance

Some bulk-fill flowable resin composites produce less cuspal deflection than a conventional incrementally filled flowable resin composites.

SUMMARY

Objective: This study investigated simulated cuspal deflection and flexural properties of bulk-fill and conventional flowable resin composites.

Methods and Materials: Five bulk-fill and six conventional flowable resin composites were evaluated. Aluminium blocks with a mesio-occlusal-distal cavity were prepared and randomly divided into groups for each of the different measurement techniques and were further subdivided according to the type of flowable resin composite. The simulated cuspal deflection caused by the polymerization of resin composite within an aluminium block was measured using a highly accurate submicron digimatic micrometer or a confocal laser scanning microscope (CLSM). In addition, the flexural properties of tested resin composites were measured to investigate the relation between cuspal deflection and flexural properties, and the resin composites were observed using scanning electron microscopy.

Results: Simulated cuspal deflection of some bulk-fill flowable resin composites was found to be significantly lower than or similar to those for conventional counterparts, regardless of the measurement method. There were

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statistically significant differences in flexural properties depending on the material, regardless of the type of flowable resin composite. Pearson correlation analysis did not reveal a statistically significant relationship between flexural properties and cuspal deflection.

Conclusion: These results indicate that some bulk-fill flowable resin composites exhibit lower cuspal deflection with the bulk-filling technique than is shown by conventional flowable resin composites using the incremental filling technique. Simulated cuspal deflection can be measured using either a micrometer or CLSM, but this experiment failed to show a significant relationship between cuspal deflection and flexural properties of flowable resin composites.

INTRODUCTION

Resin composites have come to be considered the first-choice material for direct posterior restorations because of the improvements in their mechanical properties.[1] Heintze and others[2] reported that approximately 800 million resin composite restorations were placed worldwide in 2015, with approximately 80% of them placed in posterior teeth and 20% in anterior teeth based on the quantity of restorative materials sold. Alvanforoush and others[3] reported that the overall clinical failure rates of resin composite restorations in posterior teeth were similar between 1995 and 2005 (10.59%) and between 2006 and 2016 (13.13%). In addition, the fracture rates of resin composite showed a notable increase depending on the increase in the number of cases of larger resin composite restorations in posterior teeth (1995-2005, 28.84%; 2006-2016, 39.07%) and it might be important to consider their mechanical properties when planning larger restorations. Based on the restoration failure rates, it is estimated that at least 32 million resin composite restorations that were placed in posterior teeth in 2015 will need to be repaired or replaced due to failure by 2025,[4] suggesting the importance of continuously improving the physical properties of resin composites. Therefore, manufacturers have continued to develop resin composites with enhanced physical properties.

During the formation of a highly crosslinked polymer, adequate light polymerization of resin monomers is thought to be essential to attain superior physical properties in resin composites.[5] However, volumetric shrinkage in the range of 1.5% to 5%[6] accompanies the light polymerization of resin composites because of the decrease in the distance between monomer chains owing to the conversion of weak electrostatic forces into covalent bonds. The volumetric shrinkage leads to the development of polymerization shrinkage stress as the resin composite is bonded to the tooth structures of the cavity.[7] Thus, polymerization shrinkage stress of resin composites may lead to internal and marginal gaps, microleakage, and microcracking of the tooth structure due to cuspal deflection. While studying the cause of resin composite failure, these issues associated with polymerization shrinkage should be considered.[8] Some researchers have reported that resin composites with higher mechanical properties typically demonstrate higher polymerization shrinkage stress,[9-11] which suggests that modifying the formulation of resin composites to obtain higher mechanical properties and to avoid fracture may increase the risk of problems related to polymerization shrinkage stress. While the mechanisms of polymerization shrinkage stress development within resin composite restorations are quite complex, the generation, measurement, and characterization of polymerization shrinkage stress have been researched extensively for 50 years, beginning with studies by Bowen[12] and Bowen and others,[13] and they proliferated following the work of Davidson and others[14] and Feilzer and others.[15] At present, many research laboratories are investigating the best methods for measuring the polymerization shrinkage stress of resin composites.

One of the methods for analyzing polymerization shrinkage stress of resin composites is measuring the simulated cuspal deflection using aluminium blocks with linear variable differential transformers (LVDT) developed by Park and others.[16] The advantage of this measurement method is that the cuspal deflection during polymerization of resin composites can be measured in real time. However, LVDT measurements are not widely used, and a custom-built apparatus to hold the LVDT and the specimens is required to perform these measurements. Consequently, most of the studies based on simulated cuspal deflection using LVDT have been conducted at a single research institute.[16-18] Therefore, to find an alternative to the LVDT method, the measurement of simulated cuspal deflection resulting from the polymerization of resin composite bonded to a precisely prepared mesio-occlusal-distal (MOD) cavity within an aluminium block using a novel highly accurate submicron digimatic micrometer (MDH-25M, Mitutoyo, Tokyo, Japan) or a confocal laser scanning microscope (CLSM; VK-9710, Keyence, Tokyo, Japan) was investigated in this study. Neither the microme-

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ter nor the CLSM method of cuspal deflection with an aluminium block has been used previously for this purpose; these methods may allow for more accessible measurement processes. An aluminium block (modulus of elasticity, 68.5 GPa) has been used in previous studies[16-18] to simulate cuspal deflection with polymerization of resin composites, as the mechanical properties are within the range of those for enamel (modulus of elasticity, 84.1 GPa) and dentin (modulus of elasticity, 18.5 GPa).

A previous study reported that the cuspal deflection for the incremental filling technique was considerably lower than that for the bulk-filling technique and that there was no significant difference between the horizontal and oblique incremental filling techniques.[16] Recently, using bulk-fill flowable resin composites has expedited the restoration process by enabling increments of up to 4 mm in thickness to be light polymerized, thereby avoiding the time-consuming incremental filling technique.[19] Manufacturers claim that the polymerization shrinkage stress of bulk-fill flowable resin composites may be reduced using advanced technology for the treatment of filler particles, monomer synthesis, and development of modulators to retard the polymerization rate. Therefore, using bulk-fill flowable resin composites reduces cuspal deflection even with the bulk-filling technique, when compared with that of conventional flowable resin composites using the incremental filling technique. However, few independent studies have compared the cuspal deflection between bulk-fill and conventional flowable resin composites using different filling techniques.

This study aimed to evaluate methods for measuring the polymerization shrinkage stress of bulk-fill and conventional flowable resin composites by measuring simulated cuspal deflection and to compare these values with those of flexural properties. The null hypotheses to be tested were 1) there would be no differences in simulated cuspal deflection between bulk-fill and conventional flowable resin composites, 2) there would be no differences in the cuspal deflection of resin composites measured using different methods, and 3) there would be no relationship between simulated cuspal deflection and flexural properties for any measurement method.

METHODS AND MATERIALS

Study Materials

Five bulk-fill flowable resin composites were evaluated: 1) Beautifil Bulk Flowable (BF; Shofu, Kyoto, Japan), 2) Bulk Base (BB; Sun Medical, Shiga, Japan), 3) Filtek Fill and Core (FF; 3M Oral Care, St Paul, MN, USA), 4) SDR (SD; Dentsply Sirona, York, PA, USA), and 5) X-tra base (XB; VOCO GmbH, Cuxhaven, Germany). We also evaluated six conventional flowable resin composites: 1) Clearfil Majesty ES Flow (CE; Kuraray Noritake Dental Inc, Tokyo, Japan), 2) Clearfil Majesty LV (CL; Kuraray Noritake Dental), 3) Estelite Universal Flow (EU; Tokuyama Dental, Tokyo, Japan), 4) G-ænial Universal Injectable (GI; GC, Tokyo, Japan), 5) Filtek Supreme Ultra Flowable (FS; 3M Oral Care), and 6) UniFil LoFlo Plus (UF; GC). The tested materials are listed in Table 1 with their associated lot numbers and main components.

Simulated Cuspal Deflection Measurement

Aluminum blocks (10 [W] × 8 [L] × 15 [D] mm) with an MOD cavity (4 [W] × 8 [L] × 4 [D] mm) were fabricated using a milling machine, creating two remaining cusps. The inside of the cavity was air abraded with 50 μm Al_2O_3 powder for 10 seconds to create microroughness for improved adhesion. The air pressure was set to 0.2 MPa, and the distance between the orifice and metal surface was approximately 10 mm (Jet Blast II, J. Morita Mfg Corp, Osaka, Japan). Universal adhesive (Scotchbond Universal Adhesive, 3M Oral Care) was applied prior to placing the low-viscosity bulk-fill and conventional flowable resin composites according to the manufacturer's instructions. The adhesive was light cured for 10 seconds at a standardized distance of 1 mm using a quartz-tungsten-halogen (QTH) curing unit (OptiLux 501, Demetron/Kerr, Danbury, CT, USA). The power density ($>$700 mW/cm^2) of the QTH curing unit was confirmed using a dental radiometer (model 100, Demetron) prior to specimen preparation.

The aluminium blocks were randomly divided into four groups for different measurement techniques (micrometer vs CSLM) and were further subdivided according to the type of resin composite (bulk-fill vs conventional flowable resin composite; Figure 1).

Group 1 (Micrometer × Bulk-Fill Flowable Resin Composite)—Bulk-fill flowable resin composites were placed in bulk and were light cured from the three exposed surfaces for 40 seconds each. Simulated cuspal deflection was calculated from the difference in the distance between the centers of the two remaining cusps prior to resin composite placement and 10 minutes after polymerization, as measured by a micrometer.

Group 2 (Micrometer × Conventional Flowable Resin Composite)—Conventional flowable resin com-

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Table 1: *Bulk-Fill and Conventional Flowable Resin Composites Used in This Study*

Resin Composite (Shade)	Type of Flowable Resin Composite (Code)	Resin Matrix Composition	Inorganic Filler Composition	Manufacturer (Lot No.)
Beautifil Bulk Flowable (Dentin)	Bulk-fill (BF)	Bis-GMA, Bis-MPEPP, TEGDMA, UDMA	Fluoro-silicate glass	Shofu, Kyoto, Japan (031719)
Bulk Base (Universal)	Bulk-fill (BB)	Bis-MPEPP, UDMA	Barium-silicate glass, Strontium-fluoro-alumino-silicate glass	Sun Medical, Shiga, Japan (RG12)
Filtek Fill and Core Flow (A3)	Bulk-fill (FF)	Bis-GMA, UDMA	Inorganic fillers	3M Oral Care, St. Paul, MN, USA (N863610)
SDR (Universal)	Bulk-fill (SD)	Bis-EMA, modified TEGDMA, UDMA	Barium-fluoro-alumino-silicate glass, Strontium-fluoro-alumino-silicate glass	Dentsply Sirona, York, PA, USA (1508033)
X-tra base (Universal)	Bulk-fill (XB)	Aliphatic dimethacrylate, Bis-EMA	Inorganic fillers	Voco GmbH, Cuxhaven, Germany
Clearfil Majestry ES Flow (A3)	Conventional (CE)	Hydrophobic aromatic dimethacrylate, TEGDMA	Silanated barium glass filler Silanated silica filler	Kuraray Noritake Dental, Tokyo, Japan (BA0207)
Clearfil Majestry LV (A3)	Conventional (CL)	Hydrophobic aromatic dimethacrylate, TEGDMA	Silanated barium glass filler Silanated colloidal silica	Kuraray Noritake Dental, Tokyo, Japan (850029)
Estelite Universal Flow (A3)	Conventional (EU)	Bis-GMA, Bis-MPEPP, TEGDMA, UDMA	Silica-zirconia filler	Tokuyama Dental, Tokyo, Japan (019957)
Filtek Supreme Ultra Flow (A3)	Conventional (FS)	Bis-GMA, substituted dimethacrylate, TEGDMA	Silane treated ceramic, Silane treated silica, Ytterbium fluoride	3M Oral Care, St Paul, MN, USA (N838182)
G-ænial Universal Injectable (A2)	Conventional (GI)	Bis-EMA, Dimethacrylate, UDMA	Strontium glass	GC, Tokyo, Japan (1702081)
UniFil LoFlow Plus (A2)	Conventional (UF)	Dimethacrylate, UDMA	Fluoro-alumino-silicate glass	GC, Tokyo, Japan (1702161)

Abbreviations: Bis EMA, ethoxylated bisphenol-A-dimethacrylate; Bis-GMA, bisphenol-A-glycidyl dimethacrylate; Bis-MPEPP, bisphenol A polyethoxy methacrylate; TEGDMA, triethyleneglycol dimethacrylate; UDMA, urethane dimethacrylate.

posites were placed in two horizontal consecutive layers (2 mm each). Each increment was light cured from the three exposed surfaces for 40 seconds each to ensure that an identical curing time was maintained. Simulated cuspal deflection was measured in the same manner as in group 1.

Group 3 (CLSM × Bulk-Fill Flowable Resin Composite)—Bulk-fill flowable resin composites were placed using the same method as in group 1. Simulated cuspal deflection was calculated from the distance between the center of the two remaining cusps prior to resin composite placement and 10 minutes after polymerization, as measured by a CLSM with built-in analysis software (VK-Analyzer, Keyence).

Group 4 (CLSM × Conventional Flowable Resin Composite)—Conventional flowable resin composites were placed in the same manner as in group 2. Simulated cuspal deflection was measured in the same manner as in group 3.

Flexural Properties Measurement

A Teflon split mold (2.0 [W] × 25 [L] × 2.0 [D] mm) was used to prepare the specimens, which minimized the stresses applied to the specimens during their retrieval. A condenser was used to place the resin composites into the mold. The top side of the mold was covered with a matrix strip, and the resin composites were pressed with a glass slide under a load of 5 N. The exit window of the QTH curing unit was placed against the glass plate at the center of the specimen, which was light cured for 40 seconds. Next, the exit window was moved to the section next to the center in such a way that the previous section was overlapped by approximately one-half. Light curing was performed by sequentially curing overlapping regions until the entire sample surface had been light cured. The hardened specimens were carefully removed from the mold after light curing, and silicon carbide (SiC) papers (No. 600, Struers, Cleveland, OH, USA) were used to polish the specimens to obtain smooth and flat surfaces. Fifteen specimens for each resin composite were prepared under ambient laboratory conditions of 23°C ± 2°C and 50% ± 10% relative humidity. Specimen dimensions were measured using a high-accuracy submicron digimatic micrometer, and the accepted specimen size was 2.0 ± 0.020 mm in width and height and 25 ± 0.025 mm in length. The specimens

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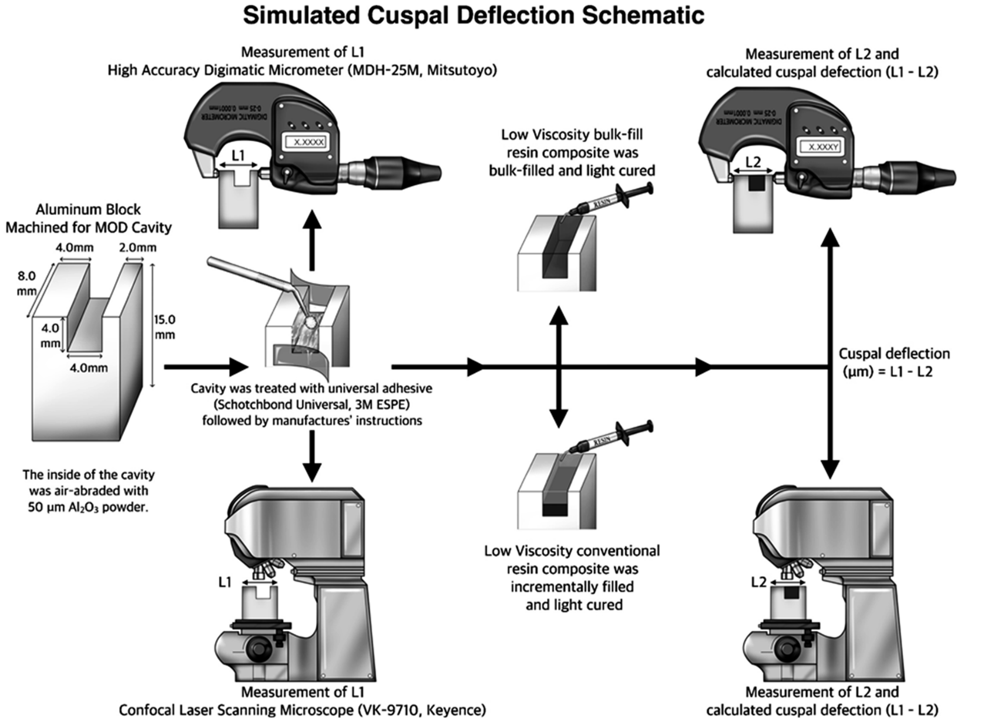

Figure 1. *Schematic drawing of the experimental setup for simulated cuspal deflection of flowable resin composites with a micrometer or CLSM.*

were immersed in distilled water in an incubator (IC802, Yamato Scientific, Tokyo, Japan) at 37°C for 24 hours.

The specimens for each resin composite underwent a three-point bending test on a universal testing machine (5500R, Instron, Norwood, MA, USA) at a crosshead speed of 1.0 mm/min until specimen fracture occurred as outlined in ISO 4049. The stress-strain curve was used to determine the flexural strength in MPa and flexural modulus in GPa using a custom software package (Bluehill 2 version 2.5, Instron) linked directly to the testing machine.

Flexural strength (σ) was calculated as follows:

$$\sigma = 3PD/2bd^2,$$

where P = maximum load at the fracture point, D = distance between the supports (20 mm), b = specimen width, and d = specimen height.

The flexural modulus (E) was calculated as follows:

$$E = P_1 D/4bd^3\delta,$$

where P_1 = the load at an intersection point within the elastic region of the stress-strain curve and δ = specimen deformation at P_1.

Scanning Electron Microscopy Observation

The polished surfaces of the resin composites underwent ultrastructural observation conducted through scanning electron microscopy (SEM). A Teflon mold with a diameter and height of 10.0 and 2.0 mm, respectively, was used to form the specimens of the resin composites. The mold was placed on a glass slide covered with a matrix strip, and the resin composites were placed into the mold using a condenser instrument. The top side of the mold was covered with a matrix strip, and the resin composites were pressed with a glass slide under a load of 5 N. The exit window of the QTH curing unit was placed against the glass slide, and the resin composite was light cured for 40 seconds. After light curing, the hardened specimens were removed from the mold and polished with SiC papers (No. 600) to obtain smooth and flat surfaces. Three specimens for each resin composite were prepared under ambient laboratory conditions at 23°C ± 2°C and 50% ± 10% relative humidity. The specimens were immersed in distilled water in an incubator at 37°C for 24 hours. After storage in the incubator, the specimen surfaces were prepared and polished using a gradually increasing sequence (No. 320, 600, 1200, 2000, and 4000) of SiC papers in a grinder/polisher (Minitech 333, Presi, Eybens, France). Finally, the surfaces were polished with

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Table 2: *Simulated Cuspal Deflection of Bulk-Fill and Conventional Flowable Resin Composites*[a]

Rank Order	Resin Composite	Type of Flowable Resin Composite	Simulated Cuspal Deflection, μm	
			Micrometer	CLSM
1	SDR (Dentsply)	Bulk-fill	7.2 (3.5)[a,A]	7.6 (1.5)[a,A]
2	Filtek Fill and Core Flow (3M Oral Care)	Bulk-fill	8.1 (1.6)[a,A]	8.2 (1.4)[a,A]
3	Bulk Base (Sun Medical)	Bulk-fill	10.9 (0.7)[b,A]	11.1 (1.0)[b,A]
4	Clearfil Majestry ES Flow (Kuraray Noritake Dental)	Conventional	15.3 (2.6)[c,A]	15.5 (0.6)[c,A]
5	UniFil LoFlow Plus (GC)	Conventional	16.0 (3.8)[c,A]	16.7 (0.9)[c,A]
6	Clearfil Majestry LV (Kuraray Noritake Dental)	Conventional	16.7 (2.1)[c,A]	17.0 (1.1)[c,A]
7	X-tra base (Voco GmbH)	Bulk-fill	17.2 (1.5)[c,A]	16.8 (1.0)[c,A]
8	G-ænial Universal Injectable (GC)	Conventional	19.8 (2.8)[d,A]	19.6 (0.8)[d,A]
9	Filtek Supreme Ultra Flow (3M Oral Care)	Conventional	20.1 (0.4)[d,A]	20.6 (1.0)[d,A]
10	Beautifil Bulk Flowable (Shofu)	Bulk-fill	20.2 (0.6)[d,A]	19.9 (0.6)[d,A]
11	Estelite Universal Flow (Tokuyama Dental)	Conventional	20.3 (2.3)[d,A]	20.3 (0.9)[d,A]

[a] *Values in parentheses are standard deviations ($n=5$). The same lowercase letter in the same vertical column indicates no significant difference ($p>0.05$). The same uppercase letter within individual rows indicates no significant difference ($p>0.05$).*

a soft cloth using 1.0-μm grit diamond paste (DP-Paste, Struers, Ballerup, Denmark). SEM specimens of the resin composites were dehydrated by first immersing them in ascending concentrations of aqueous *tert*-butanol (50%, 75%, and 95% for 20 minutes each and 100% for 2 hours) and then transferring them from the final 100% bath to a critical-point dryer (model ID-3, Elionix, Tokyo, Japan) for 30 minutes. To enhance the filler visibility, the polished surfaces were etched for 30 seconds with an argon ion-beam (Type EIS-200ER, Elionix) directed perpendicular to the surface at an accelerating voltage and ion current density of 1.0 kV and 0.4 mA/cm^2, respectively. Next, the surfaces were coated with a thin film of gold in a vacuum evaporator (Quick Coater SC-701, Sanyu Electron, Tokyo, Japan) and observed using field-emission SEM (ERA-8800FE, Elionix) with an operating voltage of 10 kV.

Statistical Analysis

Two-way analysis of variance (ANOVA) was used to analyze cuspal deflection data using the factors 1) type of resin composite and 2) cuspal deflection measurement, followed by Tukey's post hoc honestly significant difference (HSD) test with a significance level (α) of 0.05. Flexural strength and modulus data were analyzed using one-way ANOVA along with the Tukey HSD test with a significance level of 0.05. In addition, we conducted Pearson correlation analysis between cuspal deflection, using both a micrometer and CLSM, and flexural strength and modulus.

RESULTS

Simulated Cuspal Deflection

Results for the simulated cuspal deflection of bulk-fill and conventional flowable resin composites using both the micrometer and CLSM are shown in Table 2. Simulated cuspal deflection of bulk-fill flowable resin composites was material dependent, ranging from 7.2 to 20.2 μm for the micrometer and 7.6 to 19.9 μm for CLSM. In the bulk-fill flowable resin composites, SD, FF, and BB showed significantly lower cuspal deflection than did XB and BF. On the other hand, cuspal deflection of conventional flowable resin composites was also material dependent, ranging from 15.3 to 20.3 μm for the micrometer and 15.5 to 20.6 μm for CLSM. Simulated cuspal deflection of the conventional flowable resin composites was significantly higher than that for SD, FB, and BB, and most cuspal deflections were similar to those for BF and XB. A statistically significant relationship between cuspal deflection measured with the micrometer and CLSM (R=0.98, p<0.001) was seen in Pearson correlation analysis.

Flexural Properties

The results for the flexural strength and modulus of bulk-fill and conventional flowable resin composites are shown in Table 3. The flexural strength of the bulk-fill flowable resin composites ranged from 68.9 to 116.1 MPa, and the flexural modulus ranged from 2.0 to 5.3 GPa. For the conventional flowable resin composites, the flexural strength ranged from 79.9 to 132.8 MPa, and flexural modulus ranged from 3.3 to 7.4 GPa. There were statistically significant differ-

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Table 3: *Flexural Properties of Bulk-Fill and Conventional Flowable Resin Composites*[a]

Rank Order	Resin Composite	Type of Flowable Resin Composite	Flexural Strength, MPa	Flexural Modulus, GPa
1	Clearfil Majestry ES Flow (Kuraray Noritake Dental)	Conventional	132.8 (9.2)[a]	7.4 (0.5)[a]
2	G-ænial Universal Injectable (GC)	Conventional	128.8 (8.5)[a]	6.5 (0.4)[b]
3	Filtek Fill and Core Flow (3M Oral Care)	Bulk-fill	116.1 (6.7)[b]	5.3 (0.4)[c]
4	Filtek Supreme Ultra Flow (3M Oral Care)	Conventional	113.9 (7.2)[b]	5.2 (0.4)[c]
5	Estelite Universal Flow (Tokuyama Dental)	Conventional	110.6 (7.1)[b,c]	5.8 (0.4)[c]
6	X-tra base (Voco GmbH)	Bulk-fill	110.4 (6.8)[b,c]	5.0 (0.3)[c]
7	SDR (Dentsply)	Bulk-fill	105.7 (6.9)[c]	7.2 (0.5)[a]
8	Clearfil Majestry ES Flow (Kuraray Noritake Dental)	Conventional	104.7 (7.3)[c]	6.3 (0.5)[b]
9	Beautifil Bulk Flowable (Shofu)	Bulk-fill	102.1 (6.9)[c]	6.3 (0.6)[b]
10	UniFil LoFlow Plus (GC)	Conventional	79.9 (6.1)[d]	3.3 (0.3)[d]
11	Bulk Base (Sun Medical)	Bulk-fill	68.9 (5.4)[e]	2.0 (0.2)[e]

[a] *Values in parentheses are standard deviations ($n=15$). The same lowercase letter in the same vertical column indicates no significant difference ($p>0.05$).*

ences in flexural strength and elastic modulus depending on the material, regardless of the type of resin composite. The rank order was different for flexural properties and for simulated cuspal deflection. In addition, no statistically significant relationship was revealed between flexural strength and cuspal deflection on Pearson correlation analysis ($R=0.32$, $p=0.344$ for the micrometer; $R=0.33$, $p=0.334$ for CLSM) or between flexural modulus and cuspal deflection ($R=0.22$, $p=0.761$ for the micrometer; $R=0.21$, $p=0.755$ for CLSM).

SEM Observation

Representative SEM micrographs of bulk-fill and conventional flowable resin composites are shown in

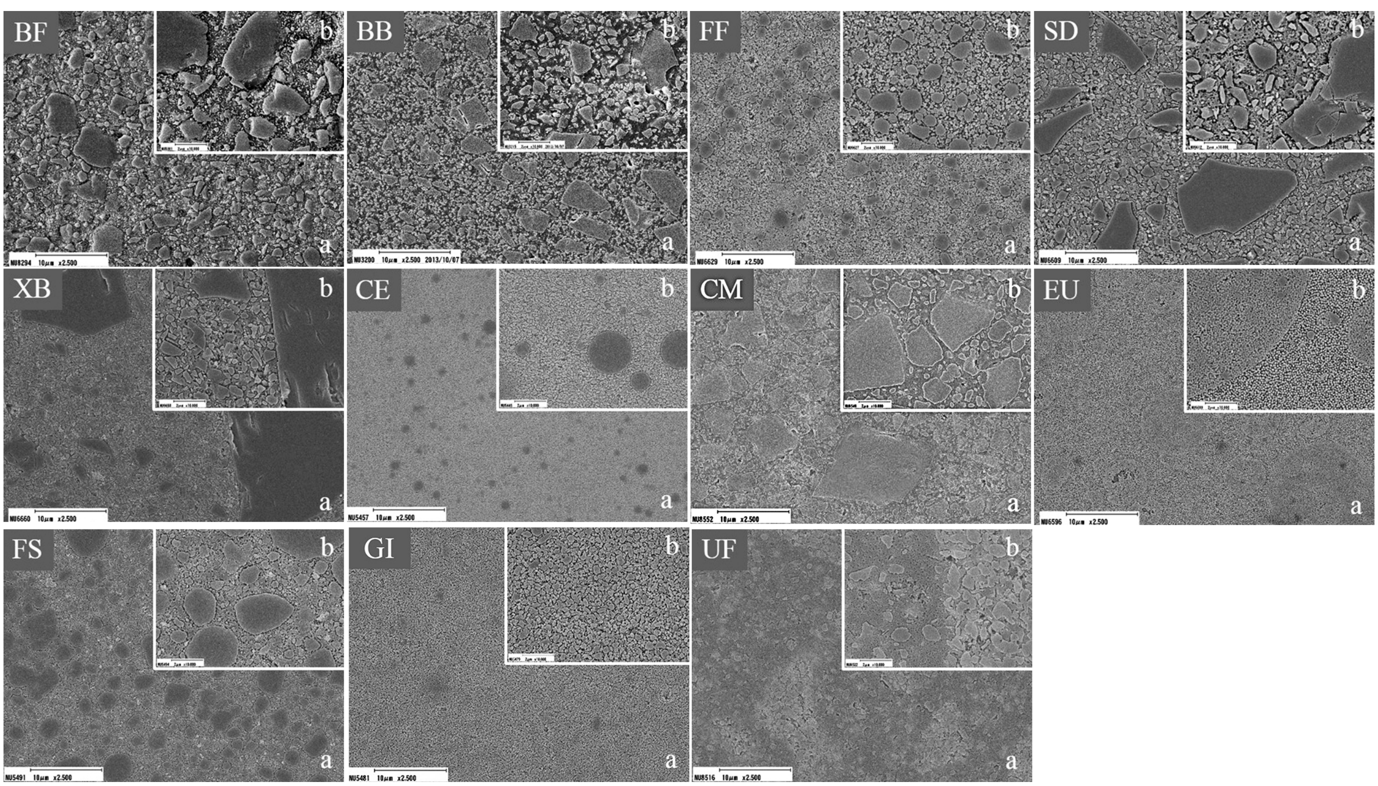

Figure 2. *Representative SEM images of the surfaces of bulk-fill and conventional flowable resin composites at (a) 2500× and (b) 10,000× magnifications. BB, Bulk Base; BF, Beautifil Bulk Flowable; CE, Clearfil Majesty ES Flow; CL, Clearfil Majesty LV; EU, Estelite Universal Flow; FF, Filtek Fill and Core Flow; FS, Filtek Supreme Ultra Flowable; GI, G-ænial Universal Injectable; SD, SDR; UF, UniFil LoFlo Plus; XB, X-tra base.*

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Figure 2. The resin composites were composed of a wide variety of fillers, and filler particle size and shape were material dependent. In the bulk-fill flowable resin composites, BF, BB, SD, and XB showed a wide size range (<1-5 μm for BF and BB, <1-20 μm for SD, and <1-30 μm for XB) of irregular-shaped fillers, and FF showed relatively uniform, small-sized (<1-2 μm) irregular-shaped fillers. In the conventional flowable resin composites, CE showed a wide size range (<1-10 μm) of irregular-shaped fillers, and CM showed nonuniform, small-sized (<1 μm) irregular-shaped fillers and small-sized (1-4 μm) spherical-shaped fillers. Nonuniform, small-sized (<1 μm) spherical-shaped fillers for EU- and irregular-sized UF-shaped fillers were observed, and some fillers were aggregated. FS showed a wide size range (<1-7 μm) of irregular-shaped fillers, and GI showed uniform, small-sized (<1 μm) irregular-shaped fillers.

DISCUSSION

Some of the bulk-fill flowable resin composites (SD, FF, and BB) used in this study showed significantly lower simulated cuspal deflection than their conventional counterparts, and the cuspal deflection of XB and BF was similar to that for most conventional flowable resin composites, regardless of the measurement system. Thus, the first null hypothesis that there would be no differences in simulated cuspal deflection between bulk-fill and conventional flowable resin composites was partially rejected. A previous study reported that the cuspal deflection of resin composites using the bulk-filling technique was significantly higher than that with the incremental filling technique regardless of type of resin composite, implying that the bulk-filling technique led to significantly more cuspal deflection than did the incremental filling technique in those experiments.[16] In the present study, the cuspal deflection of bulk-fill and conventional flowable resin composite was investigated using the filling technique specified in the manufacturers' instructions. Simulated cuspal deflection of bulk-fill flowable resin composites using the bulk-filling technique was lower than or similar to that of conventional flowable resin composites with the incremental filling technique.

The cuspal deflection of the tested resin composites was material dependent regardless of filling technique, which suggests that the cuspal deflection of resin composites is primarily influenced by their composition rather than the filling technique. In the SEM observations, a wide variation of filler type was seen in the resin composites, but there was no clear relationship between filler particle size, shape, and cuspal deflection. Although previous studies reported an effect of filler particle size and shape on shrinkage stress,[20] a systematic review of the polymerization shrinkage stress of resin composites found that modification of the resin matrix had the largest impact on minimizing stress development.[21] According to the manufacturers, SD, FB, and BB showed significantly lower cuspal deflection than did BF and XB because the resin matrix contains high-molecular-weight polymerization modulators. There was a lower ratio of functional groups for making double bonds through polymerization to molecular weight in comparison with a typical resin matrix, which is purported to reduce polymerization shrinkage.[22] Thus, the results of the present study for cuspal deflection of resin composites appeared to have been mainly influenced by the modifications of the resin matrix.

In the present study, a novel micrometer or CLSM cuspal deflection measurement method was used to measure the cuspal deflection of resin composites as a more accessible replacement for the LVDT method. There was no significant difference between the cuspal deflection measured using the micrometer and using the CLSM, and Pearson correlation analysis revealed a statistically significant relationship (R=0.98, p<0.001) between values measured with the micrometer and those measured using CLSM. Hence, the second null hypothesis that there would be no difference in the cuspal deflection of resin composites measured with different methods was not rejected.

One of the concerns with using the micrometer was the possible influence of instrument-related stress exerted on the aluminium block, while errors arising from the process of combining the scanned micrographs were a concern with CLSM; both of these factors could potentially influence the measured values. Simulated cuspal deflection measured with the micrometer ranged from 7.2 to 20.3 μm and ranged from 7.0 to 20.6 μm for CLSM. A previous study[16-18] reported that cuspal deflection measured using an aluminium block with LVDT was approximately 5-30 μm, although differences in the wall thickness of aluminium and size of the trench made direct comparison difficult.[18] If the micrometer did apply stress during the measurement period, it would be expected to cause a greater deformation of the block during the prepolymerization measurement, especially prior to resin composite filling, which would lead to a lower cuspal deflection. However, this overestimation was not observed, suggesting that stress from the micrometer was not

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a significant factor. On the other hand, stitching individual micrographs together to form a complete three-dimensional rendering from the CLSM could bias the values in either direction, but no such deviations were observed; thus, the original concerns did not appear to be justified.

During the experiment, a serious problem was noted with CLSM: it could not measure the cuspal deflection precisely after 10 minutes of polymerization because of the time required (5-8 minutes) for scanning. In this study, the measurement was conducted 10 minutes after polymerization based on a previous study; thus, the scanning duration is thought to have a minimal influence. However, the values of cuspal deflection slightly increased over a longer time period.[16-18] There is a small possibility that the cuspal deflection measured with CLSM will be higher than that with micrometer, but this was not observed in the present study. Since there was no significant difference in the cuspal deflection of resin composites measured using different methods (micrometer vs CLSM), investigators may rely on these methods for measuring cuspal deflection. In comparison with the LVDT method, the micrometer may be more accessible and easier, and CLSM may allow for more automation in the process used to measure cuspal deflection. Overall, micrometer and CLSM measurement methods of cuspal deflection of the aluminium block may be effective for evaluating the polymerization shrinkage stress of resin composite restorations. Further research is needed to determine the best experimental setup for measuring cuspal deflection as an indicator of polymerization shrinkage stress.

The flexural strength and modulus of resin composites were material dependent, but the rank order of the results was different from that of cuspal deflection. Pearson correlation analysis did not show any statistically significant relationship between flexural properties and cuspal deflection (R=0.32, p=0.344 for flexural strength and simulated cuspal deflection; R=0.22, p=0.761 for flexural modulus and simulated cuspal deflection). Therefore, the third null hypothesis that there would be no relationship between cuspal deflection and flexural properties for any measurement method was not rejected. The results of the correlation analysis do not directly support the results of earlier studies, but they are not decisive evidence against a connection.

CONCLUSION

The results of this study indicate that the simulated cuspal deflection of bulk-fill and conventional flowable resin composites can be measured using either a micrometer or CLSM. These measurements showed that some of the bulk-fill flowable resin composites used in this study had superior cuspal deflection using bulk-filling techniques in comparison with conventional flowable resin composites using incremental filling techniques. However, this experiment did not show a statistically significant relationship between the flexural properties and simulated cuspal deflection of resin composites. Further research is necessary to clarify these relationships.

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Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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