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Three-dimensional trueness and margin quality of monolithic zirconia restorations fabricated by additive 3D gel deposition☆

Rong Li[a], Hu Chen[a], Yong Wang[a], Yongsheng Zhou[a], Zhijian Shen[b,*], Yuchun Sun[a,*]

[a] *Center of Digital Dentistry, Department of Prosthodontics, Peking University School and Hospital of Stomatology, National Engineering Laboratory for Digital and Material Technology of Stomatology, Research Center of Engineering and Technology for Digital Dentistry of Ministry of Health, Beijing Key Laboratory of Digital Stomatology, National Clinical Research Center for Oral Disease 100081, Beijing, China*

[b] *Department of Materials and Environmental Chemistry, Arrhenius Laboratory, Stockholm University, S-106 91 Stockholm, Sweden*

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Purpose: The aim of this in vitro study was to evaluate the three-dimensional trueness and margin quality of monolithic zirconia restorations fabricated by additive 3D gel deposition, compared with those by subtractive milling.

Methods: Ten single crowns and ten 4-unit FPDs of different occlusal geometries and margin thickness were fabricated by additive 3D gel deposition (additive group) and subtractive milling (subtractive group). An intraoral scanner was used to digitalize the restorations. 3D deviation analysis was applied and root mean square (RMS) was used to assess the trueness. Margin quality was characterized using optical stereomicroscopy and 3D laser scanning microscopy.

Results: For single crowns with shallow fossae and grooves and normal margin, RMS value of additive group and subtractive group showed no significant difference in external surface, while additive group showed higher RMS value in intaglio surface. As for 4-unit FPDs with deep fossae and grooves and thin margin, RMS value of additive group in external surface was significantly lower than that of subtractive group and in intaglio surface there was no significant difference between two groups. With a 0.5 mm chamfer design, single crowns in additive group showed flawless margin with a smooth contour line, whereas minor flaws could be observed in 4-unit FPDs with thin margin. In subtractive group, restorations showed minor flaws or defects of various number and severity.

Conclusions: Monolithic zirconia restorations fabricated by additive 3D gel deposition have comparable trueness and better margin quality than those fabricated by subtractive milling. Besides it is more capable of enabling complex geometry.

1. Introduction

With the development of zirconia ceramics and computer-aided design and manufacturing (CAD/CAM) technology, zirconia restorations are enjoying great popularity in dental clinical practice [1].Nowadays, the dominant manufacturing method to fabricate zirconia restorations is subtractive milling of partially sintered zirconia blanks, which has been well-received due to its high trueness and cost effectiveness [2,3]. It was reported that the fabrication process plays an important role in determining the trueness and fabrication defects in the restorations [4, 5].

The trueness is crucial for the accurate seating and long-term success of restorations. An ideal trueness ensures that the seated restoration can achieve physiologically occlusal and proximal contact and, in particular, appropriate adaptation to the abutment. It is demonstrated that inhomogeneous or overlarge internal gap will adversely affect its resistance to fracture [6-8]. Poor marginal adaptation will result in microleakage, plaque retention, secondary caries and periodontal inflammation [9-11]. In addition, margin integrity is another key factor to avoid microleakage and improve load-bearing capacity of the restorations [4].

Recently, 3D gel deposition technology has been applied to fabricate zirconia ceramics [12]. Studies on the 3D gel deposition-fabricated zirconia reveal that, with no need for polishing or glazing, it presents a smooth surface and dense fine-grained microstructure, and its wear performance is demonstrated to be comparable to well-polished zirconia fabricated by conventional sub-

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* Corresponding authors.
E-mail addresses: shen@mmk.su.se (Z. Shen), kqsyc@bjmu.edu.cn (Y. Sun).

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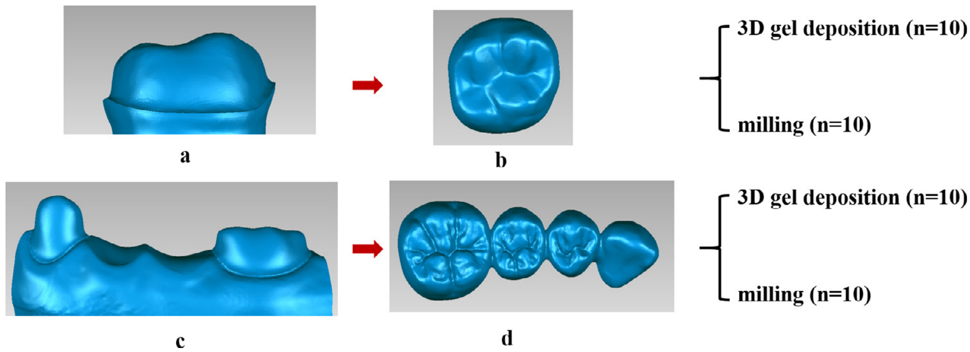

Fig. 1. Illustration of restoration design and fabrication. Crown: (a) abutment with a chamfer of 0.5 mm (b) occlusal geometry of shallow fossae and grooves; 4-unit FPD: (c) abutment with a mini-chamfer of 0.3 mm (d) occlusal geometry of deep fossae and grooves.

tractive manufacturing [12,13]. A new grade of monolithic zirconia restoration, known as self-glazed zirconia, has been developed. It is produced by additively depositing the zirconia gel to form a green body, followed by a milling procedure over the intaglio surface. The trueness and margin quality of this grade of monolithic zirconia restoration have not yet been characterized in any details.

The aim of this in vitro study was to evaluate the three-dimensional trueness and margin quality of monolithic zirconia restorations fabricated by additive 3D gel deposition, compared with those by conventional subtractive milling of partially sintered blanks. The null hypothesis was that there would be no differences in trueness between different fabrication processes.

2. Materials and methods

2.1. Tooth preparation and design of full-contour restorations

Crowns and 4-unit FPDs of different occlusal geometries and margins were designed. Digital models of tooth 16 and a dentition defect with tooth 34, 35 missing and tooth 33, 36 serving as abutments were achieved by scanning dental model (Nissin Dental Products, Kyoto, Japan). Teeth were digitally prepared in a reverse engineering software (Geomagic Studio 2013, Raindrop, NC, USA), with an occlusal reduction of 1.0 to 1.5 mm and a taper of 6 to 10°. The abutment for crown was prepared with a circumferential chamfer of 0.5 mm (Fig. 1a), which is commonly recommended for zirconia restoration. As for 4-unit FPD, the abutment was prepared with a circumferential mini-chamfer of 0.3 mm (Fig. 1c), corresponding to a thin restoration margin.

Based on the prepared abutments, full-contour crown with shallow fossae and grooves (Fig. 1b) and 4-unit FPD with deep fossae and grooves (Fig. 1d) were designed using 3Shape Dental System 2015 (3Shape A/S, Copenhagen, Denmark). The design models (CAD data) were saved as standard tessellation language (STL) files and exported for manufacturing.

2.2. Fabrication of monolithic zirconia restorations

Ten single crowns and ten 4-unit FPDs were made by each fabrication process. In additive group, the monolithic restorations were fabricated by 3D gel deposition (Self-glazed zirconia, ErranTech, Hangzhou, China). A hybrid gel based on 3 mol% yttria-stabilized tetragonal zirconia nanoparticles was prepared and additively deposited on dies to form a near net shape green body with accurate external surface, followed by a milling procedure over the intaglio surface to refine the internal surface and margin. All the fabricated single crowns and 4-unit FPDs were sintered to full density at 1450 °C for 2 h. In subtractive group, restorations were fabricated by subtractive milling of partially sintered zirconia blanks (Katana ML A light, Kuraray Noritake, Tokyo, Japan). According to the manufacturer, the blank was shaped by cold-isostatic pressing (CIP) of 3 mol% yttria-stabilized tetragonal zirconia polycrystal powders, followed by a partial sintering procedure. In the present study, a 5-axis milling machine (250i, imes-icore, Eiterfeld, Germany) was used to fabricate restorations from the zirconia blanks. All restorations were then sintered to full dense at 1500 °C for 2 h. No additional manual adjustments were performed.

2.3. Digitization and 3D trueness analysis

All the fabricated single crowns and 4-unit FPDs were cleaned and dried. The external and intaglio surfaces were scanned respectively by an intraoral scanner (3Shape TRIOS 3,3Shape A/S, Copenhagen, Denmark).

The scan data were imported to a reverse engineering software (Geomagic Studio 2013, Raindrop, NC, USA) in STL format. For each group, scan data of external and intaglio surfaces were aligned to the CAD data respectively in the following strategy and analyzed.

Firstly, “Manual Registration- n-point Registration” was performed by manually defining pairs of corresponding points on each model (CAD data and scan data) and then aligned. In defining the points, points of characteristic feature (such as points in cusp tip and fossa area) and of a dispersed distribution over the model were chosen for a better preliminary alignment of the CAD data and scan data (Fig. 2).

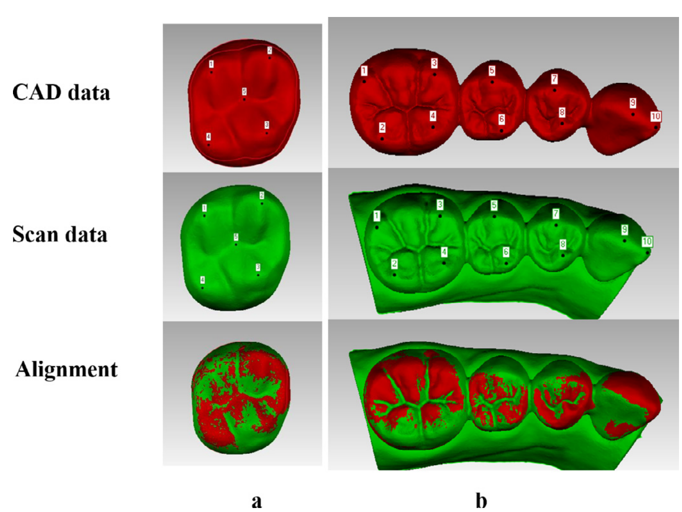

Fig. 2. Manual Registration: pairs of corresponding points on CAD data (red) and scan data (green) were defined to achieve a preliminary alignment. (a) crown; (b) 4-unit FPD.

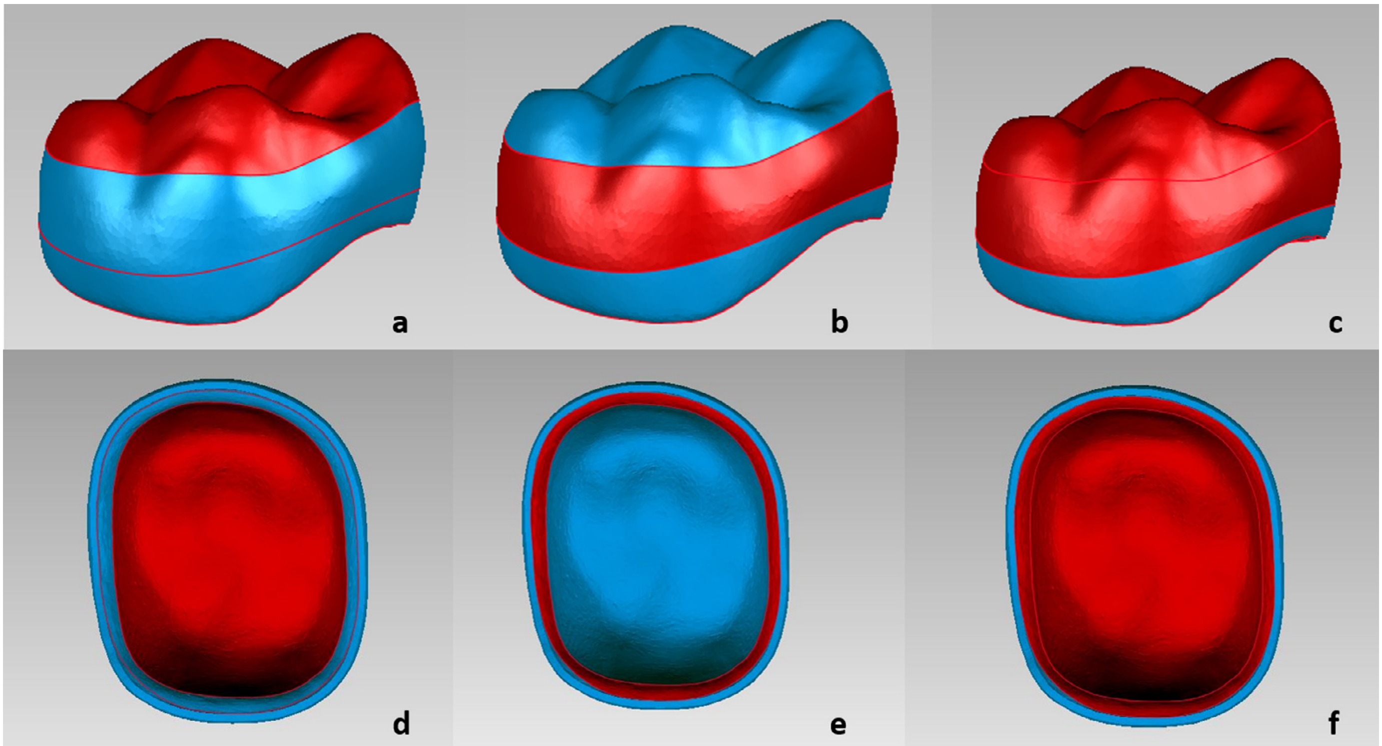

Fig. 3. Crown: For external surface analysis, (a) occlusal and (b) mid-axial areas were defined; For intaglio surface analysis, (d) internal and (e) marginal areas were defined. Best fit alignment was performed by simultaneously selecting the defined areas (c, f).

Secondly, areas of interest were selected for further alignment. For external surface, occlusal (Fig. 3a, Fig. 4a) and mid-axial (Fig. 3b, Fig. 4b) areas which are clinically relevant to occlusal and proximal contact were selected simultaneously (Fig. 3c, Fig. 4c) and "Best Fit Alignment" was performed. "Best Fit Alignment" is based on an iterative closest point (ICP) algorithm and it aligns models by minimizing the mesh distance error between each corresponding data point [14]. In this way, a higher number of points were used to optimize the alignment. For intaglio surface, internal (Fig. 3d, Fig. 4d) and marginal (Fig. 3e, Fig. 4e) area were selected and the same strategy for alignment was performed.

3D deviation analysis was performed to detect the distance between scan data and CAD data in each selected area. Color-difference map was generated and the root mean square(RMS) was calculated according to the following formula [15].

$$\mathrm{RMS} = \frac{\sqrt{\sum_{i=1}^{n} (X_{1,i} - X_{2,i})^2}}{\sqrt{n}}$$

Where $X_{1,i}$ is the measuring point i in CAD data, $X_{2,i}$ is the measuring point i in scan data, and n is the total number of measuring points.

RMS indicates how far deviations between two different datasets vary from zero [15] and it is a general method to assess the mean value of errors by directly comparing two datasets within an identical coordinate system [16]. A low RMS value indicates a high dimensional trueness of the fabricated restoration.

2.4. Margin quality

Each restoration was examined at 5 × magnification by an optical stereomicroscope (SZX7, OLYMPUS, Tokyo, Japan) for margin defects and graded on a scale of 1–5 according to the number and severity of defects, which was developed by Schriwer et al. [4] for evaluating margin quality. As follows,1: Smooth edge with no defects;2: Smooth edge with few, small separate defects;3: Several small defects;4: Rough edge with continuous defects;5:Large defects. Observation by 3D laser scanning microscope (VK-X200, Keyence, Osaka, Japan) was applied for detailed characterization. The scanning was carried out in 1024 × 768 pixel resolution up to an area of approximately 1.4 × 1 mm² at 200 × magnification and pictures were recorded for documentation.

2.5. Statistical analysis

Statistical analysis was performed using SPSS (IBM SPSS Statistics 19, IBM, Armonk, USA). RMS values were positively tested for normal distribution. Differences between the additive group and subtractive group were analyzed using Student's *t*-test. Level of significance was set at 0.05.

3. Results

Trueness analysis results were shown in Table 1. For single crowns with shallow fossae and grooves and normal margin, additive group and subtractive group showed no significant difference in external surface, while additive group showed higher RMS value in intaglio surface ($P<.05$), including internal and marginal area. As for 4-unit FPDs with deep fossae and grooves and thin margin, RMS value of additive group in external surface was significantly lower than that of subtractive group and in intaglio surface there was no significant difference between two groups. Representative color-difference map of 3D deviation analysis was shown in Fig. 5, presenting major positive error in deep fossae and grooves and in connector section.

Table 2 shows the result of evaluation by optical stereomicroscope observation at 5 × magnification. With a 0.5 mm chamfer design, every crown in additive group showed smooth edge with no defects, while 2/10 crowns in subtractive group were found to

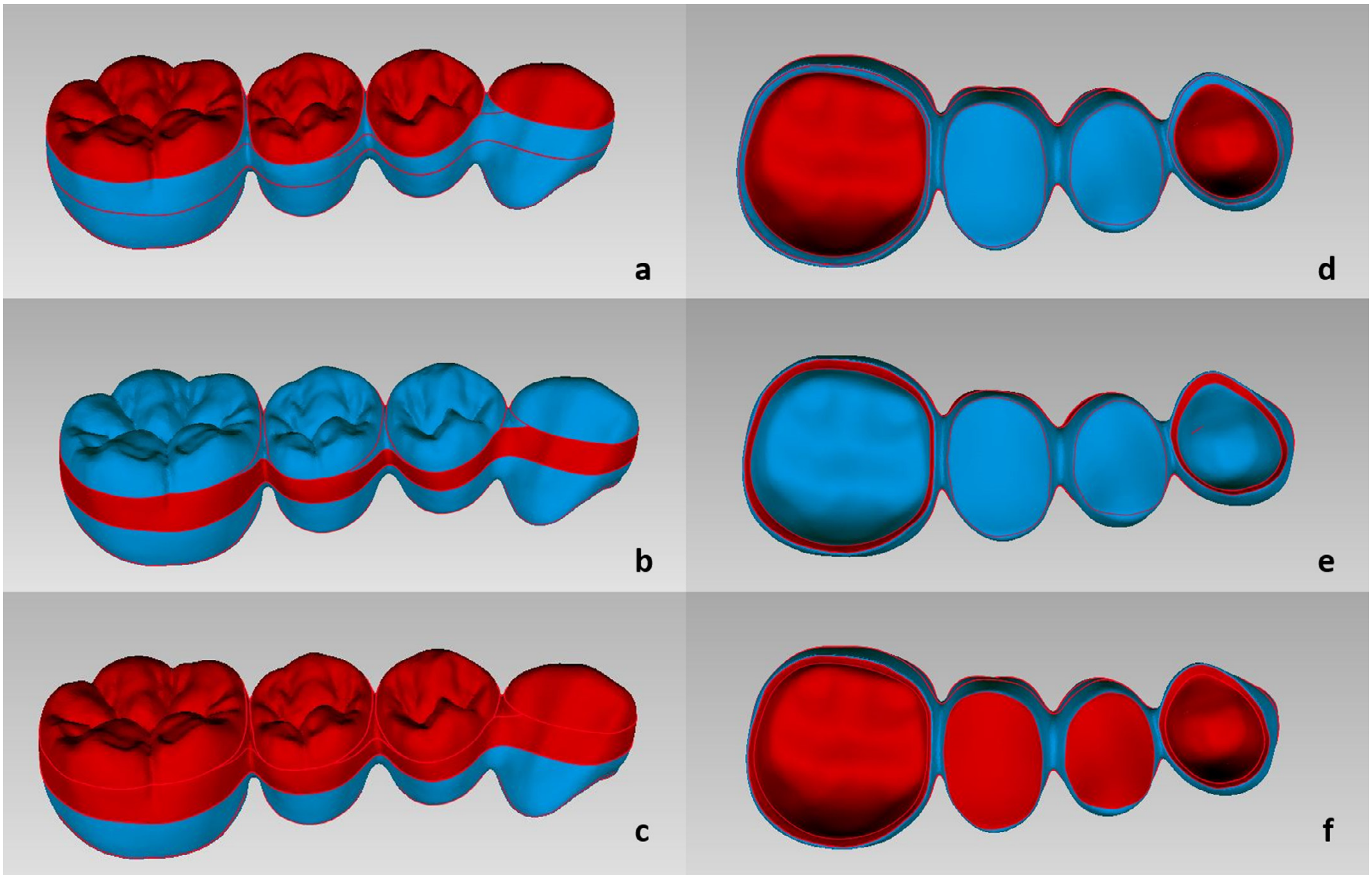

Fig. 4. 4-unit FDP: For external surface analysis, (a) occlusal and (b) mid-axial areas were defined; For intaglio surface analysis, (d) internal and (e) marginal areas were defined. Best fit alignment was performed on simultaneously selecting the defined areas (c, f).

Table 1
Trueness based on RMS of the fabricated restorations, Student's *t*-test($n = 10$).

Area	additive group $\bar{x} \pm s$, μm	subtractive group $\bar{x} \pm s$, μm	*P*
Single crown			
Occlusal-crown	13±3	11±2	.216
Axial-crown	20±5	20±3	.896
Internal-crown	16±3	13±1	.024
Marginal-crown	22±4	18±2	.048
4-unit FPD			
Occlusal-FPD	28±3	33±2	.001
Axial-FPD	30±3	41±3	<.001
Internal-FPD	19±3	17±4	.255
Marginal-FPD	21±6	23±6	.301

Table 2
Margin quality evaluation: the number of each grade ($n = 10$).

Grade	Crown (0.5 mm chamfer) additive	subtractive	4-unit FDP (0.3 mm chamfer) additive	subtractive
1: Smooth edge with no defects	10	8	9	0
2: Smooth edge with few, small separate defects	0	2	1	4
3: Several small defects	0	0	0	1
4: Rough edge with continuous defects	0	0	0	1
5: Large defects	0	0	0	4

have small separate defects. For 4-unit FDP with a 0.3 mm chamfer, 1/10 in additive group showed small separate defects while those fabricated by milling all showed defects of various number and severity. Further observation by 3D laser scanning showed that crowns in additive group(Fig. 6a) showed a defect-free margin with smooth contour line at 200 × magnification while minor flaws were detected in milling groups(Fig. 6b). For 4-unit FPDs with thinner margin, flaws were detected in both group(Fig. 6c,6d). Large defect in subtractive group was characterized in Fig. 6e,6f.

4. Discussion

This in vitro study was aimed to evaluate the three-dimensional trueness and margin quality of monolithic zirconia restorations

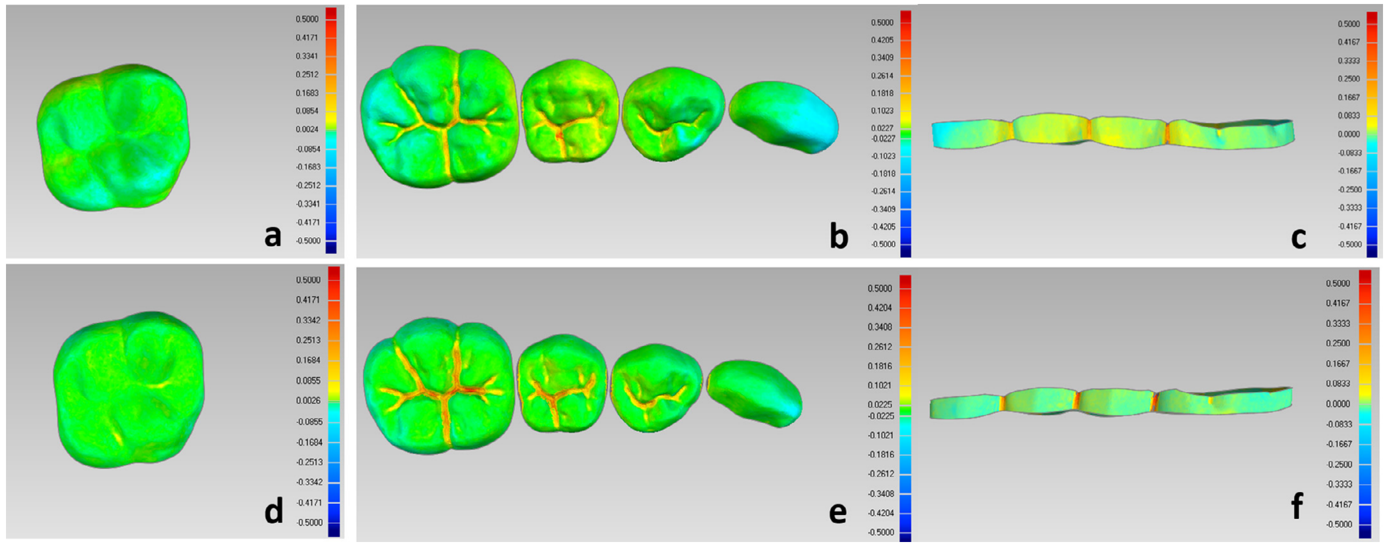

Fig. 5. Representative color-difference map of 3D deviation analysis. Additive group: (a, b) occlusal area (c) axial area; Subtractive group: (d, e) occlusal area (f) axial area. Red indicates positive error, blue indicates negative error, and green indicates relatively good trueness.

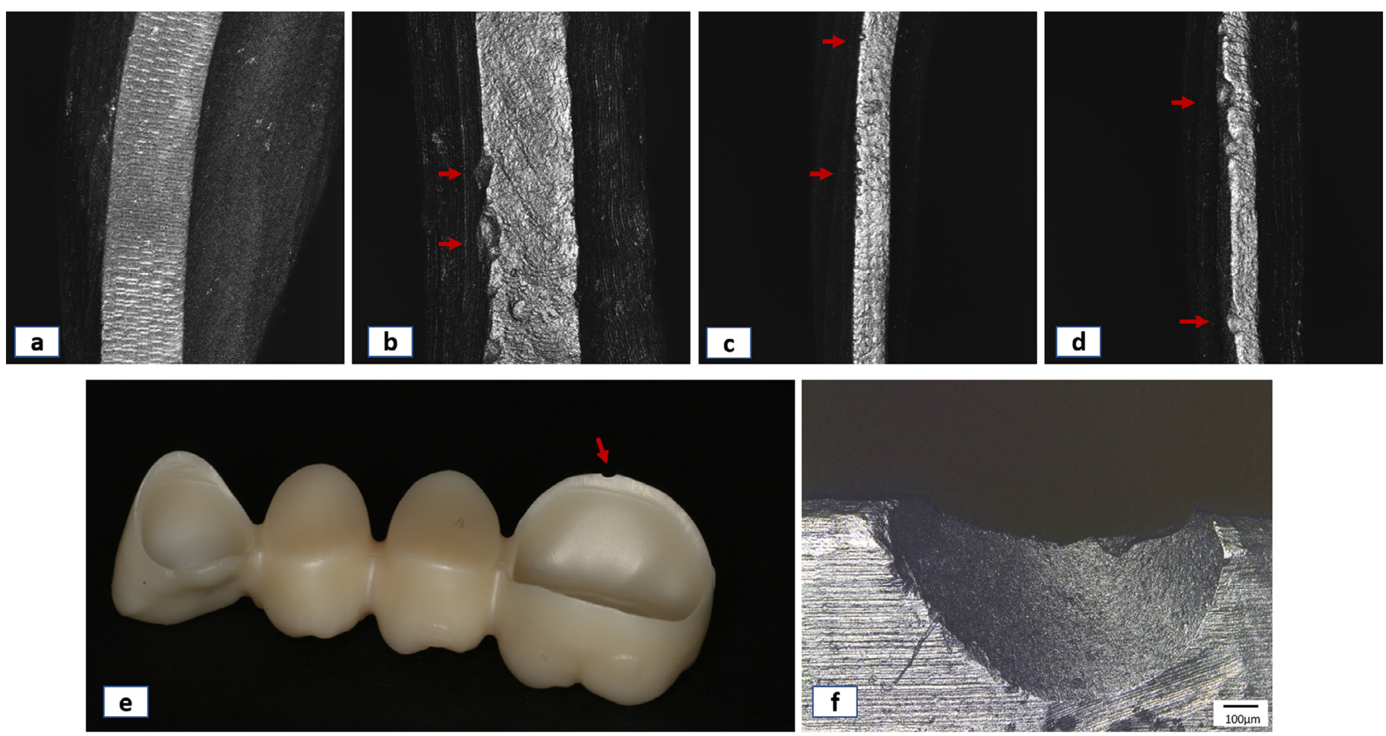

Fig. 6. Representative margins of the fabricated restorations under 3D laser scanning microscope. Single crown: (a) additive group (b) subtractive group; 4-unit FPD: (c) additive group (d) subtractive group; (e) macroscopic defect found in 4-unit FPD of subtractive group and (f) the corresponding microscopic picture.

fabricated by additive 3D gel deposition, compared with those by conventional subtractive milling of partially sintered blanks. The null hypothesis was rejected, indicating that fabrication process does affect trueness of dental restorations.

Various methods can be applied to evaluate the accuracy of restorations, such as direct inspection of the marginal gap with a probe or under microscope [17], duplicating the gap with silicone replica and then performing cross-section measurement [18] or 3D digital analysis [19]. These methods are all restricted to analyze the internal and marginal fit of restoration, while the method applied in the present study makes it possible to perform quantitative analysis of the entire restoration. It is non-destructive, requiring no silicone replica and thus can avoid the potential error caused by deadhesion of silicone from the abutment. Furthermore, in contrast to conventional evaluation methods with limited measurement points, the 3D analysis of trueness can provide a much larger measurement sample size, depending on the digitizing system and area chosen for analysis [20,21]. In the present study, measurement points add up to approximately 14,000 per crown and 36,000 per 4-unit FDP.

By applying a similar trueness-analysis method, Wang et al. reported a 3D trueness of milled zirconia single crowns of 52±18 μm for external surface, 43±12 μm for intaglio surface and 35±7 μm for marginal area [22]. Kang et al. obtained a trueness of PMMA provisional crowns fabricated by subtractive manufacturing of 31.8 ± 7.5 μm for outer surface and 14.6 ± 1.2 μm for inner surfaces [23]. The RMS values in the present study (from 13±3 μm to 30±2 μm) are within the range of the reported results and tend to be smaller. This can be attributed to differences in study design and fabrication process. However, it is worth noting that scanner used in the reported studies is cast scanner which requires powdering over crown surfaces. The powdering procedure tends to result in a higher RMS values due to the thickness of powder coating. Besides, it is tricky for experimenter to make sure the coating is thin enough, and meanwhile, uniform all over the surface and among groups to minimize the error introduced. The intraoral scanner applied in this study can avoid the application of powdering and is reported to has high accuracy [24-26].

When fabricating the single crown with normal margin and shallow fossae and grooves, additive group and subtractive group showed no statistically difference in RMS value of external surface, including occlusal and axial area. Color-difference maps indicate only small positive error in few grooves area in subtractive group. When applied in fabricating the 4-unit FPDs with thinner margin and deep fossae and grooves, 3D gel deposition obtained a RMS value of 28±3 μm in occlusal area and 30±3 μm in axial area while milling obtained a RMS value of 33±2 μm in occlusal area and 41±3 μm in axial area. Color-difference maps showed red color in deep fossae and grooves for occlusal area (Fig. 5) and in connector section for axial area, corresponding to a major positive error. This result is consistent with those reported in previous studies [22,27,28]. The higher RMS value in subtractive group indicates a lower trueness. It reflects the limitation of conventional subtractive milling process, which is, due to the restriction of size and shape of the milling bur, details of small concave shape cannot be manufactured with high accuracy. The higher trueness of additive group indicates that additive 3D gel deposition is more capable of fabricating complex geometry, such as deep fossae and grooves, with high accuracy.

In additive group, a milling procedure was adopted to machine over the intaglio surface of the green bodies with near net shape formed by 3D gel deposition to improve clinical adaptation. Difference of RMS value in intaglio surface between two groups can be attributed to different milling parameters which are recommended by the manufacturers. Yet, such a difference of 2–4 μm in mean RMS value between the two groups is acceptable for clinical application. It is noteworthy that marginal area of FDPs in subtractive group showed the highest RMS value. Combined with the results of margin quality observation, this highest RMS value is ascribed to the large processing defects.

Margin quality is recognized to affect the long-term performance of restoration during its clinical service and increasing margin integrity can reduce the risk of both biological and technical complications [4]. The formation of margin defects is related to the material composition, margin design and the applied manufacturing method [4,5,29]. The present study focused on comparing on the margin processing capability of the two manufacturing methods. This comparison was performed by fabricating crowns with normal margin design and 4-unit FDPs with thin margin design. Results showed that additive group achieved better marginal quality, presenting almost defect-free margin with a 0.5mm-chamfer design and only few minor microscopic margin defects with a thin-margin design. In subtractive group, restorations showed minor flaws or defects of various number and severity. Large defects occurred in 4-unit FDPs with a thin margin in subtractive group make the restorations no longer clinically applicable.

In conventional subtractive manufacturing, the restorations are milled form a blank and it is estimated that approximately 90% of a prefabricated blank is removed during the milling process [30]. Such an intensive milling process is potentially to introduce machining stress and flaws to the restoration [31], especially in margin of a small thickness. Furthermore, in subtractive group the zirconia blank is milled at a partially sintered chalk-like stage [1], in which unwanted material is removed by peeling off agglomerates of zirconia powder, but hardly individual particles [12]. This way of material removal tends to form minor flaws in margin area. Schriwer et al. assessed margin quality of monolithic zirconia dental crowns, including six commercially brands, and results show soft-machined crowns all have margin flaws [4],which consents with results in the present study. In additive group, the green bodies were formed by additive 3D gel deposition and further milling over the intaglio surface was performed to refining the restorations from near net shape to net shape, meaning the involvement of very limited amount of milling. In addition, milling in green stage enables the material to be removed in a much finer way even by local plastic deformation. The resulting machining stress is distinctly lower than that generated in conventional subtractive milling of partially sintered blanks.

This study has limitations. First, the abutment used is a standard model, which is different from the clinical condition. Moreover, effects of the margin flaws or defects on the fracture resistance of restorations need to be further investigated.

5. Conclusions

Within the limitation of this study, the following conclusions are drawn:

1. Monolithic zirconia restorations fabricated by additive 3D gel deposition have comparable trueness than those fabricated by conventional subtractive milling of partially sintered blanks, whereas 3D gel deposition is more capable of enabling complex geometry, such as deep fossae and grooves.
2. Additive 3D gel deposition can fabricate restorations with margin quality better than those achieved by conventional subtractive milling of partially sintered blanks.

Declaration of Competing Interests

None.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jpor.2020.01.002.

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