Effect of frame design on the fracture strength of a zirconia crown and porcelain-faced crown

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In this study, we investigated the effect of frame design on the fracture strength of a zirconia crown and porcelain-faced crown, with the aim of clinically applying a zirconia crown fabricated using computer-aided design and manufacturing. The results showed that the fracture strengths were 645.9 MPa with Frame Design 1, 759.5 MPa with Frame Design 2, and 989.7 MPa with Frame Design 3, suggesting that the fracture strength improved depending upon the frame design. The above information suggests that it is necessary for the zirconia crown frame form to have an occlusal surface table where the crown design has a reduced outer diameter, instead of using the conventional form of covering the abutment tooth with a thickness of 0.5 mm.

Keywords: CAD/CAM, Porcelain, Zirconia, Frame design, Fracture strength

INTRODUCTION

Recently, the computer-aided design (CAD)/computer-aided manufacturing (CAM) system has emerged from technological innovations in dental treatment[1-5]. With this technique, high-strength ceramics have been used clinically as an alternative material for reinforcement, which was previously accomplished by metal. Zirconia has garnered much attention as a restoration material. Zirconia is needed because it has superior biocompatibility compared to metal and has better aesthetics than a metal frame[6-9]. A clinical problem with this technique is the chipping of, and damage inflicted upon, the porcelain facing the zirconia crown due to occlusal force. In much of the research to date, reports have indicated that the mechanical properties of zirconia are equal to or superior to those of metal. However, if we consider the device's function as a long-term prosthetic device under mastication, it is essential to measure its fracture strength, while taking into consideration its clinical form and the unfavorable intraoral environment[10-13]. Previous studies have analyzed occlusal contact damage-associated fracture behavior for zirconia crowns[14] and have demonstrated the utility of supportive designs and supportive regions in frame designs when loads are applied to the occlusal surface at various points[15]. However, few studies have compared the fracture strengths and fracture morphologies in by built-up porcelain with different frame designs after being subjected to the static load; thus, little is known about this aspect. Therefore, we considered it necessary to compare the fracture strength when frame designs are provided to fracture strength when they are not provided. Furthermore, based on previous studies, we have hypothesized that the safest zirconia frame design is one that enables uniform build-up of porcelain by reducing the outer crown diameter and that reduces the stress of static load on porcelain veneer by providing an occlusal surface table. These features may serve as safety guidelines for the production of zirconia crown frame forms.

In this study, we aim to clarify the design of the optimal supporting shape for long-term functional use inside the mouth for porcelain-facing zirconia crowns. We investigated differences in frame morphologies that affected the fracture strengths of zirconia crowns and porcelain veneer crowns. The present study also analyzed porcelain veneer fractures.

MATERIALS AND METHODS

Materials

The materials used for the experiment were as follows: zirconia ceramics: nano zirconia P-nano ZR (Full sintered, Panasonic Healthcare, Tokyo, Japan) and dedicated porcelain for zirconia frame: vintage ZR (SHOFU, Kyoto, Japan).

Methods

1. Specimen production

The abutment tooth die model (SUS304, Japan Meec, Tokyo, Japan, hereinafter referred to as die) used in the experiment and the schematic illustration of dimensions are shown in Figs. 1a, b. The abutment tooth die marginal form had a 1 mm wide round shoulder. The basal plane diameter was 9 mm, occlusal surface diameter was 6 mm, height was 6 mm, and the taper was set at 8°. The die was given a curved surface with a curvature radius

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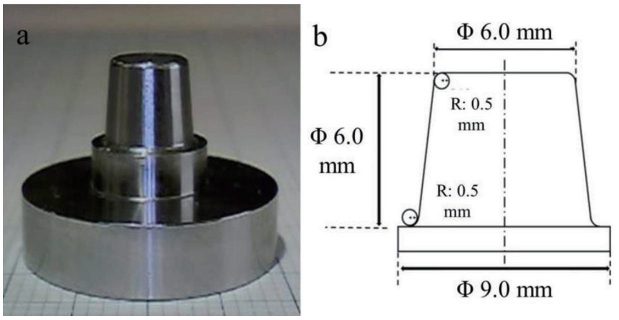

Fig. 1 The die model (a) and schematic illustration of dimensions.

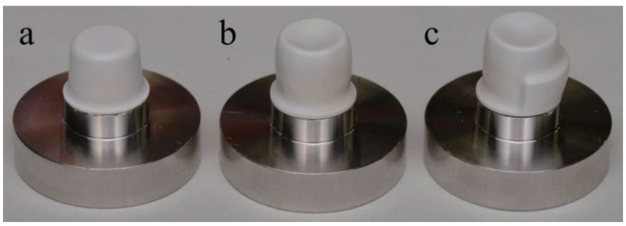

Fig. 2 Wax designs of the zirconia frame.
a: Design 1, b: Design 2, c: Design 3

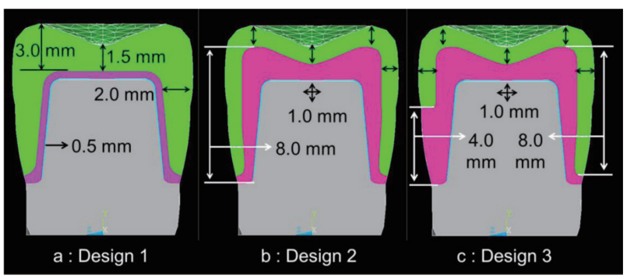

Fig. 3 Designs of the zirconia frame (red) and porcelain-faced crown (green).
a: Design 1, b: Design 2, c: Design 3

of 0.5 mm on the corners.

To manufacture the zirconia frame the crown was waxed up on the mold (Mighty Wax, SHOFU) and the frame was fabricated by cutting back from the wax crown (Fig. 2 a–c). The frame form had a 0.5 mm-thick covering on the die for Design 1 (D1: a); Design 2 had a reduced form with a 1 mm-thick outer crown (D2: b); and Design 3 was a form with an occlusal surface table around half the crown, which was half the length of the crown used for Design 2 (D3: c) (Fig. 3 a–c). At this time, the porcelain-faced crown thickness was cut back uniformly to 1 mm. A CAD/CAM system (3Shape, Copenhagen, Denmark) was used to process the zirconia frame. The processing method used the double scan method and the outline data of the three forms of the wax frames was scanned. The die model created with a shape measuring instrument (3Shape Dental Designer, 3 Shape) used

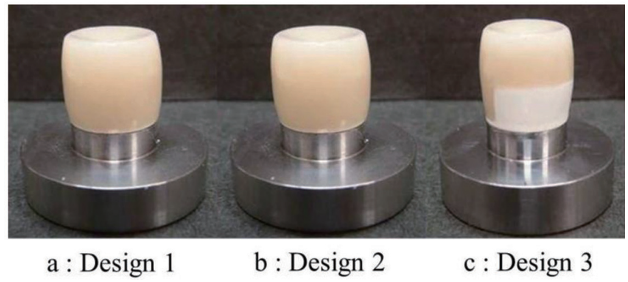

Fig. 4 Test specimen of zirconia frame and porcelain-faced crown.
a: Design 1, b: Design 2, c: Design 3

the stereolithography (STL) data produced with three-dimensional (3D)-CAD software (CATIA, Dassault Systemes, Paris, France), rather than the scanned die data. The zirconia frame was subsequently carved out with a processor (C-Pro System milling machine, Panasonic Healthcare). As pre-treatment, the processed zirconia frame underwent alumina sandblasting with a particle diameter of 50 µm and 0.4 air pressure. It was then heat treated at 1,000°C for 5 min. The dedicated porcelain for zirconia frame vintage ZR was used to build up the porcelain. First opaque porcelain was built up and fired, and then the crown outline was further with dentin porcelain. It was essential that the crown outline had the identical form, so a silicon guide was fabricated based on the wax-up. The porcelain was built up three times and underwent condensing with a ceramic condenser ceramosonic S (SHOFU), in all the processes, to suppress shrinkage and air bubble formation during the porcelain firing. The surface properties were then modified in the following order: recontouring, polishing, and glazing.

The crown was fitted onto the abutment tooth die after ultrasonic cleaning, Rocatec treatment of the inner surface of the crown, and application of ceramic primer (Cleafil Ceramic Primer, Kuraray Noritake, Tokyo, Japan), using Panavia F2.0 (Kuraray Noritake). Eight specimens were fabricated for each of the three forms. A total of 24 specimens were made (Fig. 4).

2. Test methods

The fracture test measured the loading at the point the specimen fractured with a loading speed of 0.5 mm/min, adding a vertical load to the central fovea using an indenter with a 6 mm diameter ball-shaped tip using a material testing machine (Servopulser EHF-FD1, SHIMADZU, Kyoto, Japan). The value obtained by dividing the surface area in contact with the zirconia crown directly under the load was set as the fracture strength. The experiment was randomly implemented a total of 24 times.

3. Scanning electron microscopy

The specimen after the fracture test was coated with osmium with an osmium coater (Neoc-AN, Meiwafosis, Tokyo, Japan), and photographed focusing on the interface between the zirconia frame and the porcelain and the fracture morphology directly under the load using a scanning electron microscope (SEM; S-4000, HITACHI, Tokyo, Japan) at 20 kV. The photographs were evaluated.

4. Fracture strength

From the measurement results, the cumulative probability of failure was obtained using the median rank approximation formula shown below and statistical processing was conducted using log-normal probability paper. In other words, the fracture strength and cumulative probability of failure were plotted on the horizontal and vertical axes of the log-normal probability paper, respectively, and the fracture strengths were compared. The cumulative probability of failure was calculated using the following formula:

$P=(i-0.3)/(n+0.4)$

P: cumulative probability of failure,

i: fracture test number in ascending order,

n: total number of test pieces

5. Statistical analysis

From the results, after confirmed to have equal variance, a one-way analysis of variance (ANOVA) was used for statistical processing in conformity with the above factors and levels. Tukey's multiple comparison test was employed when a significant difference was found ($p<0.05$).

RESULTS

Fracture strength

Figure 5 shows the statistical distribution of the effect of the frame design on the fracture strength of zirconia crowns and porcelain-faced crowns, plotted on normal distribution paper. The slopes of the straight lines plotted on normal distribution paper decreased as fracture strength increased (in the order of D1, D2, and D3). The fracture strength was 645.9 (SD: ±186.8) MPa with D1, 759.5 (SD: ±66.4) MPa with D2, and 989.7 (SD: ±24.1) MPa with D3. The fracture strength increased in the order of D1, D2, and D3, and Design 3, which demonstrated the highest strength was a form with an occlusal surface table around half the crown which was half the length of the crown used for Design 2. The results of Tukey's method for multiple comparisons found significant differences between D1 and D3, D2 and D3, but no significant difference was found between D1 and D2. The results of one-way analysis of variance indicated a significant difference ($p<0.01$) in the effect of different frame designs on fracture strength. The 95% confidence interval (Qi) was ±78.4 MPa.

SEM analysis

1. Fracture morphology observations

The D1, D2, and D3 fracture morphologies are shown in Figs. 6a–d. With D1 (Fig. 6a), all the specimens demonstrated a mixed fracture, where the porcelain-faced crown fractured from close to the tip of the loading point and fractured from the zirconia frame interface part (arrow). With D2 (Fig. 6b), the form demonstrated cohesive failure with part of the porcelain-faced crown fracturing from the tip of the loading point and a crack propagating from the tip of the loading point (Fig. 6c). With D3 (Fig. 6d), separation of the porcelain-faced crown was not observed in any of the specimens and a crack propagated from the tip of the loading point.

2. Observation with SEM

The fracture morphology as observed ceria- using SEM is shown in Fig. 7. With D1, the porcelain-faced crown had fractures in the entire area of the crown, beginning from the tip of the loading point (Fig. 7a). On the fracture surface of the magnified portion of the specimen, there were multiple fracture origins near the tip of the loading point, as well as slip lines. A smooth fracture surface

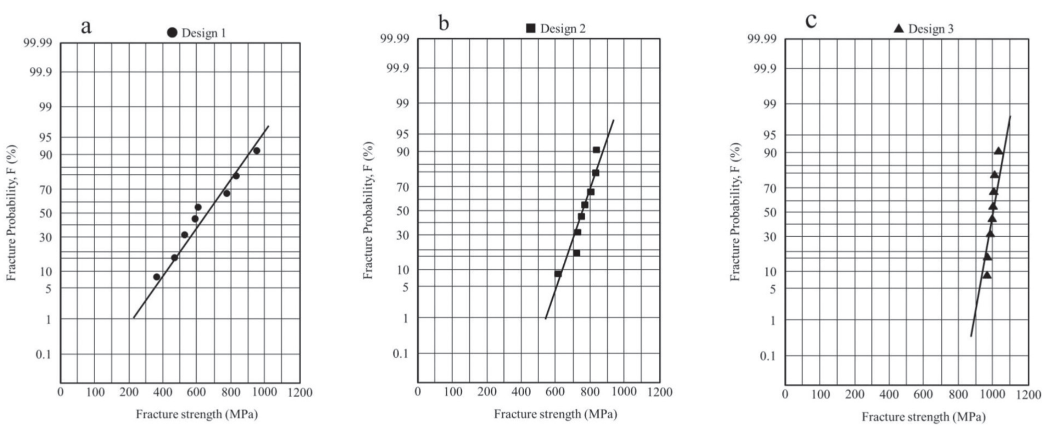

Fig. 5 Cumulative probability plots of Fracture strength of a specimen of the zirconia frame and porcelain-faced crown on the normal probability paper.
a: Design 1 at Static load test, b: Design 2 at Static load test, c: Design 3 at Static load test

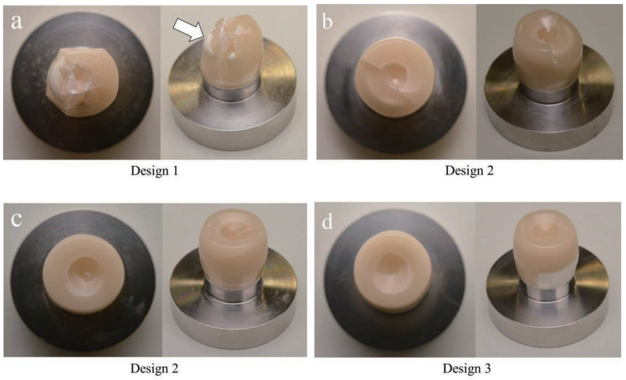

Fig. 6 Photographs of the fractured surface on the zirconia frame and porcelain-faced crown after the static load test.
a: Fracture surface of specimen imparted with Design 1. b: Fracture surface of specimen imparted with Design 2 (cracked porcelain). c: Fracture surface of specimen imparted with Design 2 (fractured part of porcelain). d: Fracture surface of specimen imparted with Design 3.

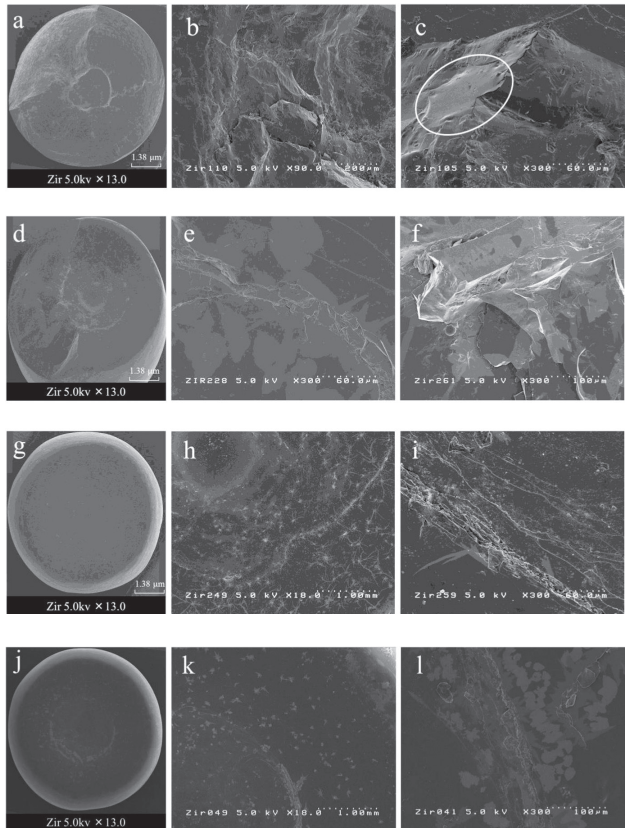

Fig. 7 SEM micrographs of the fractured surface on the zirconia frame after the static load test.
a–c: SEM micrograph of fractured on porcelain after static load of Design 1. d–f: SEM micrograph of fractured on porcelain after static load of Design 2 (cracked porcelain). g–i: SEM micrograph of cracked on Porcelain after Static load of Design 2 (fractured part of porcelain). j–l: SEM micrograph of cracked on porcelain after static load of Design 3.

(circled), specific to brittle material, was also observed (Figs. 7b, c). In a part of the fracture specimen of D2, radial cracks were observed beginning from the tip of the loading point (Fig. 7d). Several cracks had formed in a row, and the fracture occurred along the surface of the crack in the magnified portion of the specimen (Fig. 7e). On the fracture surface, similar to D1, the fracture origin, slip line, and a smooth surface specific to brittle material were observed (Fig. 7f). In the D2 specimen with cracks only, radial cracking was seen starting from the tip of load point (Fig. 7g). On the partially magnified surface of the specimen, many fine cracks propagated from outside of the loading point, and a larger number of cracks (Fig. 7h) were observed than in the partially fractured specimen (Fig. 7e). The propagating cracks had fractured from the surface to the deep portion, and the degree of cracking was harsh (Fig. 7i). With D3, radial cracks were observed starting from the tip of the loading point, and fine cracks were observed around the outside of the load point (Fig. 7J). There were fewer (Fig. 7h) and finer and shorter cracks, which propagated radially, than those in the D2 specimen with cracks only (Fig. 7i). There was also a reduction in the fine cracks outside the load point (Fig. 7k).

DISCUSSION

In this study, we compared two types of support shapes against a conventional shape for clarifying the design of the optimal supporting shape for long-term functional use inside the mouth for porcelain-facing zirconia crowns.

It is important for prostheses fitted in the mouth to retain an esthetic quality and enable long-term functional use.

The results of this study indicate that the zirconia frame form had significantly greater fracture strength than the conventional form simply by adding color to the frame, and the zirconia frame having a support shape with an occlusal surface table around half the crown length and half the crown periphery had a further increase in fracture strength. The fracture strength of the zirconia frame with a support shape was greatly superior to that of the conventional shape; hence, the presence or absence of a support shape and differences in the support shape affected the fracture strength of porcelain-facing zirconia crowns. As a result of building up the porcelain veneer to a uniform level and taking the anatomical shape into consideration, the fracture morphology changed from showing separation of the porcelain veneer to having only cracks in the porcelain veneer. Based on this result, designing a framework having a support shape with an occlusal surface table around half the crown length and half the crown periphery where the porcelain veneer is built-up to a uniform level, while taking the anatomical shape into consideration, enabled the acquisition of a suitable support for the porcelain veneer.

The nano zirconia P-nano ZR used in this study is a ceria-based stabilized zirconia and alumina composite material. It has a higher flexural strength and fracture toughness value than yttria-based zirconia[16,17]. In current clinical practice, it is used in prosthetic treatment, such as for bridges with 2 to 4 teeth. It is also reported that there is almost no occurrence of the low-temperature degradation seen in yttria-stabilized zirconia[18-20]; therefore, it is stable enough to be used long-term in the harsh oral environment. In conventional all-ceramic restorations, it is generally necessary to remove 1.0 to 2.0 mm from the abutment tooth, but with P-nano ZR, it is possible to manufacture thin frames of 0.3–0.5 mm for adhesive bridges and some crowns. For this reason, the amount removed from the abutment tooth is reduced, resulting in a less invasive all-ceramic restoration with little burden on the patient. With these superior properties, it is possible to secure a strong frame, even with a thickness of 0.5 mm, which enables porcelain-faced prosthetic restoration by providing the frame design; therefore, we used P-nano zirconia ZR for crown frame material.

The study hypothesized that the location subjected to loading would be the mandibular first molar. We fabricated three types of crown frame designs that were was based on porcelain fused-to-metal crowns traditionally used in clinical practice and still used to this day. We considered methods to investigate the effect of a difference in crown frame design that the application of zirconia would have on the porcelain-faced crown fracture strength[21-23].

The survival rate of the zirconia crown has been investigated since its first use in clinical practice. It is significantly lower than the porcelain fused-to-metal crowns, with many of the failed cases resulting from separation or desorption of the porcelain-faced crowns; there are no reports on the failure of the frame itself[6,7]. In clinical practice, the frame design must also take aesthetics, such as translucency and color reproducibility[24], into consideration. Therefore, 0.3–0.5 mm is the frame thickness that maintains strength while not detracting from the aesthetics. These frame designs are shaped with a uniform frame thickness based on the form of the abutment tooth[25]. This form caused the load to be on the porcelain-faced crown, rather than on the frame; therefore, adding the load and stress to the built up porcelain, which resulted in fracturing of the porcelain-faced crown. In addition, the porcelain-faced crown fractures occurred at the site where the porcelain became thicker.

With the porcelain-faced crown fracture seen in D1 in this experiment, the fracture occurred at the thicker part of the porcelain directly under the load point. The fracture line propagated to as far as just below the corner of the zirconia frame, in the same manner described in previous literature[26,27]; thus, the porcelain-faced crown fracture was a cohesive failure and a mixed fracture, since the fracture occurred at the interface with the frame (Fig. 6, D1). In the SEM observations, there were multiple cracks and a smooth slip line-like fracture surface within the fracture line. There were no fracture aspects observed to indicate that the frame design exerted a strong vertical load on the porcelain-faced crown.

The fracture strength increased from 645.9 MPa with D1 to 759.5 MPa with D2, increasing by 113.6 MPa. Porcelain-faced crown fractures and cracks were confirmed in fracture morphology observations. On examination using SEM, there were no interface fractures observed; instead, mainly a cohesive failure was observed. The D2 form dispersed the vertical load, and the porcelain could be built up as uniformly as possible with a frame design that contracted the stress directly under the load, thus reducing the stress in the porcelain-faced crown[28-30], as well as the risk of porcelain-faced crown fracture and/or separation.

The fracture strength increased from 759.5 MPa with D2 to 989.7 MPa with D3, increasing by 230.2 MPa. Only a crack in the porcelain-faced crown was detected in fracture morphology observations. On examination using SEM, it was observed that the cracks directly under the load point were also significantly reduced. D3 has a form like D2, and additionally has a having a saucer-like frame design. Thus, it is possible that that the occlusal plane walls bore the stress of the vertical load. This is believed to have prevented the fractures from developing. In the conventional form, strong loading on a thick porcelain-faced crown propagated the load to the frame corners, which became the fracture origin for porcelain separation and fracture. Therefore, with D3, by providing an occlusal surface table around half the crown, we were able to improve fracture prevention[31].

Zirconia-based all-ceramic crowns have been the subject of numerous materials studies and thriving solid-state physics research. Bending strength and firing time of zirconia frames and porcelain veneers have been studied extensively, leading to the development of crowns and bridges that can be used in clinical settings. However, since these crowns have started being used in clinical situations, zirconia frame and porcelain veneer fractures have been reported. In order to improve this situation, studies have been conducted to optimize frame design and analyze frame mechanics; these studies have yielded more stable clinical outcomes, which have been applied in creating new frame designs. However, studies on static load and frame design will likely not yield any further major developments. Going forward, it will be necessary to analyze dynamics using three-dimensional finite element analysis in models with support designs. By focusing on dynamic loading and occlusal relationships, it will be important to obtain clinical outcomes for crowns with support designs provided to the frames, and to closely examine their relationship with each other.

CONCLUSIONS

The present study examined the effect of frame design on the fracture strength of porcelain-faced crowns and zirconia crowns fabricated using CAD/CAM; the fracture strength was demonstrated to increase. Instead of using the conventional design with an abutment tooth 0.5 mm in thickness, it was shown that a zirconium crown frame design having an occlusal surface table with a reduced outer crown diameter is extremely effective in enabling long-term use of oral prostheses without damage to the porcelain veneer or the frame.

CONFLICT OF INTEREST

KURODA, SHINYA and GOMI declare that they have no conflict of interest.

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