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Original article

Retentive force of telescopic crowns combining fiber-reinforced composite and zirconia

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Abstract

Purpose: This study investigated changes in the retentive force of telescopic crowns fabricated by combining a zirconia primary crown and a fiber-reinforced composite (FRC) secondary crown.

Methods: Primary zirconia crowns were produced with a nominal convergence angle of 0°. Forty-eight secondary crowns were milled from FRC and divided into three study groups (n=16/group) based on milling parameters and post-milling adjustment. The offset parameter used for the final milling step of the inner crown surface was adjusted for a tight initial fit in Group 1 (milling offset: +10 µm, i.e., 2 × 10 µm = 20 µm lower inner diameter compared with the CAD file of the crown) and for improved initial fit (milling offset: -10 µm, i.e., an enlargement of the inner crown diameter by 2 × 20 µm = 40 µm in relation to Group 1) in Groups 2 and 3. The inner surfaces of the secondary crowns were polished with diamond paste in Groups 1 and 2, and silicon points were used for Group 3. The retentive force was measured using a universal testing device. The secondary crown was placed on the primary crown, with the final fitting force set to a load of 100 N. This test was conducted before and after aging (10,000 insertion/removal cycles) under dry and wet conditions. A generalized linear model was used to estimate the differences in the retentive force to elucidate the effects of the milling parameters and polishing methods.

Results: We realized an initial retentive force of approximately 10 N. In Groups 2 and 3, the difference was statistically significant between the dry and wet conditions before aging ($P < 0.05$). There was no significant difference between the dry and wet conditions after aging in any of the groups ($P > 0.05$).

Conclusion: An adequate initial retentive force can be achieved with telescopic crowns combining zirconia and FRC.

Keywords: Removable partial denture, CAD/CAM, Telescopic crown, Retention, Fiber-reinforced composite

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1. Introduction

Double crowns are retainers for removable partial dentures, and they may be used with both natural teeth and implants [1]. A double crown is a retainer that allows the occlusal force to be effectively transmitted along the axis of the abutment tooth [2], maintains the hygiene status of the abutment tooth, and optimizes the load on both the abutment tooth and the residual ridge during biting and chewing [3]. Numerous studies have demonstrated a high survival rate for the abutment teeth of double crowns [4-9], and there is also the advantage that repairs and adjustments, as required for instance in the event of the loss of an abutment tooth [10], can be easily done.

Metal-based double crowns have conventionally been hand-fabricated by skilled dental technicians using the lost wax technique [11], but the efficiency of fabrication has been improved by the application of computer-aided design and computer-aided manufacturing (CAD/CAM) [12]. Danielczak et al. reported a method of double crown fabrication in which the primary (inner) and secondary (outer) crowns were designed using a computer and milled from cobalt-chromium (CoCr) alloy disks by computer numerical control (CNC) [13].

In addition, advances in CAD/CAM technology have made it possible to process a range of different materials, and various attempts have been made to fabricate double crowns using materials other than alloys [14-17].

For example, double crowns made from the combination of a zirconia primary crown and an electroformed gold secondary crown have been widely fabricated, and their performance has been demonstrated in numerous clinical reports and studies [18-21]. Zahn et al. performed a prospective long-term trial, with non-metallic secondary crowns made of composite resin reinforced with glass fibers (fiber-reinforced composite, or FRC) [22], but the glass fiber and the matrix resin were sourced separately, and manual fabrication work

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using a conventional working model was needed. Compared to electroformed secondary crowns, the risk of damage was significantly higher for FRC secondary crowns. In recent years, FRC resin disks for CAD/CAM use have become available, and they have been used for fixed partial dentures and implant superstructures [23,24]. Therefore, the use of FRC in secondary crowns of a double crown must be investigated. Two methods have been proposed for correcting the conformity of the secondary crown to the primary crown. The first method is to make the secondary crown with a tight fit and adjust the retentive force by adjusting the inner surface of the secondary crown. The second method was to produce the correct fit through milling alone.

Therefore, herein, we investigated changes in the retentive force of telescopic crowns fabricated by combining a zirconia primary crown and an FRC secondary crown following a repeated insertion/removal test. We formulated the null hypotheses that there would be no difference in retention 1) between test groups according to milling parameters or polishing method and 2) within test groups due to aging (repeated crown insertion and removal) or surface condition (dry/wet).

2. Materials and methods

2.1. Telescopic crown fabrication

A working model of the maxilla (Frasaco, Tettnang, Germany) was selected as a simulation model. The plastic artificial central incisor, canine, second premolar, and second molar on both sides were prepared as abutment teeth for primary crowns, resulting in eight different abutment teeth. The prepared artificial teeth were replicated in zirconia; the replicas were scanned using a dental lab scanner (D2000, 3Shape, Copenhagen, Denmark), and the primary crowns were then designed on these replicas using a dental system (3Shape). Primary crowns for the eight abutment teeth with a convergence angle of 0° were milled from zirconia disks (Cercon ht, Cercon Brain Xpert, DeguDent, Hanau, Germany) and sintered in a Cercon heat plus sintering furnace (DeguDent). The completed primary crowns were bonded to the zirconium abutment teeth with adhesive resin cement (Panavia F 2.0, Kuraray, Hattersheim, Germany) to produce specimens of abutment teeth fitted with primary crowns. These teeth were then fixed in place in stainless steel molds using acrylic resin (Technovit 4071, Heraus Kulzer, Hanau, Germany) (**Fig. 1**). Later, these molds enabled standardized positioning of the sample teeth in the testing devices for repeated insertion/removal tests and measurements of the retentive force.

Subsequently, the primary crowns were ground and polished with a parallel milling machine (Fraesgeraet-F1, Degussa, Frankfurt, Germany), and the final wall thicknesses never fell below a priori defined threshold 0.6 mm. The real convergence angle of the primary crowns was determined according to the method proposed by Schwindling et al. [16]. After grinding and polishing of the primary crowns, they were coated with a scan spray and digitized using a laboratory scanner. Then, the best fitting parameter set for the insertion direction and a constant convergence angle was calculated using scalar products of the axis direction, and all normal vectors of the triangles on the retentive crown surface weighted with the respective triangle areas.

Based on the scans of the primary crowns, secondary crowns were designed for the dental system (Dental Designer, 3shape). The designs were specified with a minimum wall thickness of 1.0 mm and no gap (0 µm for both marginal gap and cement gap) between the primary and secondary crowns. In addition, a cylindrical pin was added to the occlusal surface after cutting the secondary crown´s top off with a horizontal plane (Geomagic DesignX, Rock Hill, SC, USA). This standardized geometry allowed for crown fixation in sample holders compatible with all testing devices used. The secondary crowns were milled from an FRC disk (TRINIA, BICON, Arborway, Boston, MA, USA) using a CNC milling machine (PrograMill7, Ivoclar Vivadent, Schaan, Liechtenstein). Three test groups were differing in milling parameters and/or post-milling adjustment/polishing of the inner crown surface. Group 1 had a tight initial fit (offset parameter during milling: +10 µm, i.e., the inner crown diameter was decreased by 2 × 10 µm = 20 µm in relation to the CAD construction file, which is the standard for the milling process) and was polished with diamond paste (Geomagic DesignX, Rock Hill, SC, USA). Group 2 had a slightly enlarged inner crown diameter (offset parameter during milling: -10 µm, i.e., an enlargement of the inner crown diameter by 2 × 20 µm = 40 µm compared with Group 1) for improved initial fit and was polished in the same manner as Group 1. For Group 3, the same milling procedure was used as for Group 2, but polishing was carried out with silicon points (CompoMaster, Shofu, Kyoto, Japan). The retention of the crowns was adjusted by a dentist until retention in the dry state was between 5 N and 15 N (the targeted initial retentive force was 10 N), and the time needed for adjustment was recorded. Each of the 16 crowns (two sets for each of the eight abutment teeth) was fabricated for each test group, resulting in a total of 48 secondary crowns. The completed secondary crowns were stored in distilled water at 37 °C for 1 week prior to the retentive force measurements.

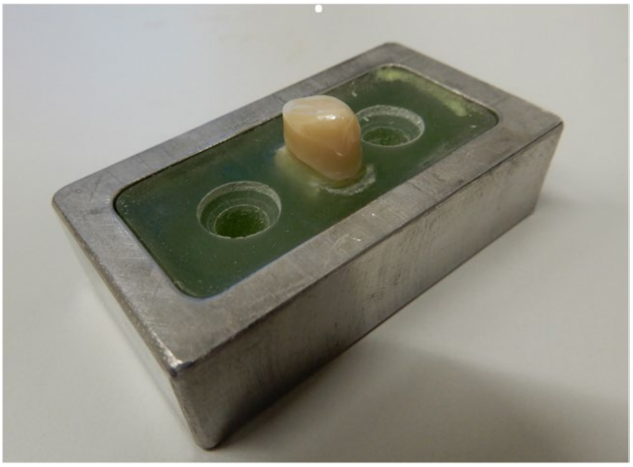

Fig. 1. Primary crowns were embedded in steel molds with a vertically oriented insertion direction.

2.2. Retentive force measurements

The retentive force was measured using a universal test device (Zwick/Roell Z005, Zwick, Ulm, Germany) (see **Fig. 2**). The test setup incorporated a spherical joint below the mold to compensate for small inaccuracies in the axis alignment of the primary and secondary crowns, as well as a ball bearing, eliminating unwanted horizontal forces. Weight was necessary to provide the requisite reaction force during crown loosening without lifting the sample from the ball bearing (**Fig. 3**). We tested different fitting force magnitudes (F_{max} = 25 N, 50 N, 75 N, 100 N) in ascending order in our experiments to identify the state at which the secondary crowns reached their re-

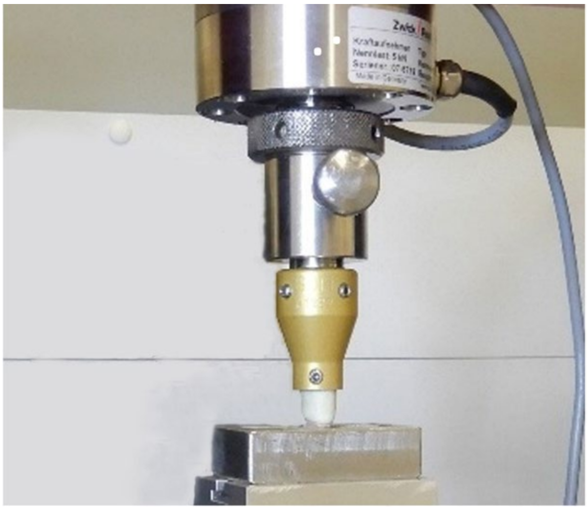

Fig. 2. All samples were tested in a universal testing device with a fitting force of 100 N.

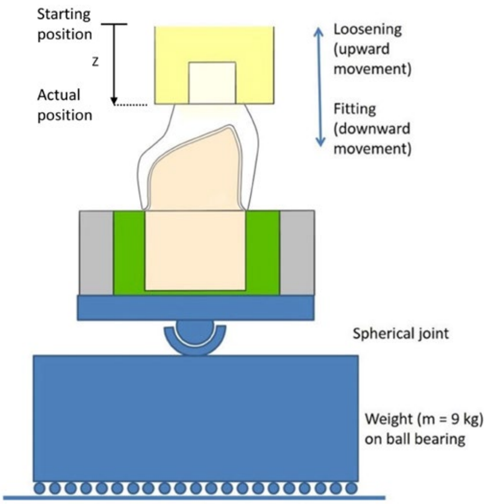

Fig. 3. Schematic of the test setup with the secondary crown attached to the cross-bar and the primary crown fixed on a weight such that horizontal forces were excluded.

spective final (vertical) positions relative to the primary crowns. Up to this point, retention increased. However, when using even higher fitting forces beyond this state, the retention remained almost constant. For the telescopic crowns tested in this study, a final load of 100 N was always sufficient for reaching this steady state. The displacement was measured from the start position at which a slight gap existed between the primary and secondary crowns (loosened state). In the first phase of each retention test cycle, the primary and secondary crowns were fitted with the actual fitting force magnitude, F_{max}. In the second phase, the secondary crown was lifted from the primary crown to the start position with a crosshead speed of 1 mm/min, and the maximum force required for loosening was considered to be the retentive force. **Figure 4** illustrates this procedure for a typical sample and a final fitting force magnitude F_{max} = 100 N. An increasing fitting force has been generated as the secondary crown moved downward, toward the primary crown. After the fitting force magnitude F_{max} = 100 N was reached, the secondary crown moved upward until a loosening force was generated. When

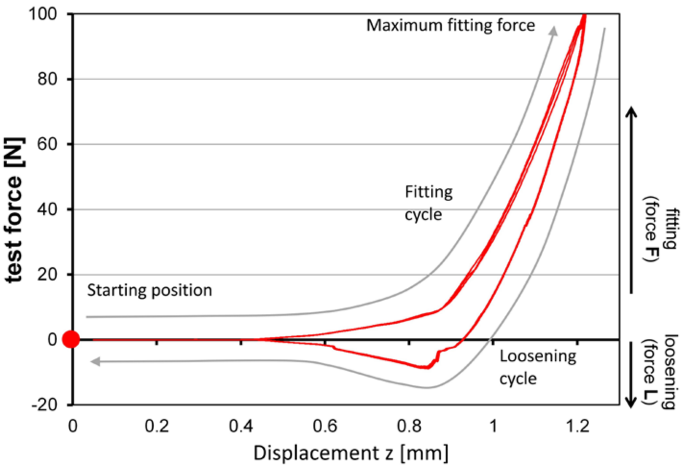

Fig. 4. A representative force-displacement diagram of the retention tests with 3 fitting/loosening cycles.

Fig. 5. Artificial aging of specimens after transfer to a chewing simulator. During artificial aging, both insertion (with 53 N of force magnitude) and removal of the crowns took place with a crosshead speed of 30 mm/s.

reaching the starting position, the primary and secondary crowns were separated. The retentive force was measured before and after artificial aging (repeated insertion/removal tests) under dry and wet conditions. Dry conditions were achieved by drying the primary and secondary crowns with oil-free air. For the wet condition, a thin water film was added to the primary crown surface before the first phase.

2.3. Artificial aging

Repeated insertion/removal tests were performed as an artificial aging method for the double crown assembly with a total of 10,000 insertion/removal cycles using a chewing simulator (CS-4; SD Mechatronik, Feldkirchen-Westerham, Germany) (see **Fig. 5**). Primary crown surfaces were kept wetted with distilled water and were therefore not immersed in water, which could have stopped the fitting process. In the chewing simulator, a mass of 4 kg was applied at a velocity of 30 mm/s via a spring-damper system (spring stiffness of 43 N/mm, damping constant of 135 N s/m), resulting in a fitting force of 53 N (static force of 39 N). Loosening of the secondary crown occurred during the upward movement of the crosshead at a speed of 30 mm/s [16].

2.4. Microscopic observation

The inner surface of the secondary crowns was examined using a scanning electron microscope (SEM; JSM 6510, JEOL, Tokyo, Japan) for an evaluation of the ultrastructure.

2.5. Statistical analysis

For each of the four combinations of repeatedly measured parameters, i.e., the surface condition (dry/wet) and aging (before/after), a general linear model (GLM) was used to estimate the differences in retentive force according to the independent factors of the milling parameters and the polishing method (SAS V9.4; SAS, North Carolina, USA). Changes between the test groups during repeated measurements were analyzed using the Wilcoxon signed-rank test (SPSS V25; IBM, New York, USA). Statistical analyses were performed using the significance level set to 0.05.

3. Results

The adjustment time was 13.1±3.3 min/crown in Group 1, 7.9±6.2 min/crown in Group 2, and 8.9±5.0 min/crown in Group 3. **Figure 6** shows that the initial retention of all crowns after adjustment (before aging) and in dry conditions was in the range of 5–15 N, as specified in the Materials and Methods section, with only slight differences between the test groups.

Under dry conditions, the initial retentive force ranged between 2.5 N and 14.0 N (median 9.8 N) in Group 1, 4.7 and 10.3 N (median 7.7 N) in Group 2, and 5.2 N and 14.8 N (median 9.0 N) in Group 3. Under wet conditions, the range of the initial retentive forces was 1.8–26.0 N (median 10.0 N) in Group 1, 3.3–15.1 N (median 9.3 N) in Group 2, and 8.3–23.8 N (median 15.1 N) in Group 3. In Groups 2 and 3, the difference between dry and wet conditions was statistically significant (Group 1: $P = 0.569$, Group 2: $P = 0.022$, Group 3: $P > 0.001$). Under dry conditions, the retentive force after aging was 1.7–21.5 N (median 11.5 N) in Group 1, 0.9–10.8 N (median 4.6 N) in Group 2, and 0.1–7.5 N (median 2.6 N) in Group 3. Under wet conditions, the retentive force after aging was 0.7–24.9 N (median 7.4 N) in Group 1, 0.9–14.7 N (median 3.4 N) in Group 2, and 0.3–8.7 N (median 2.5 N) in Group 3. There was no statistically significant difference in retentive force after aging for all groups between dry and wet conditions (Group 1: $P = 0.125$, Group 2: $P = 0.57$, Group 3: $P = 0.801$). When comparing retention before and after aging, it can be seen that mean retention remained approximately constant for Group 1, whereas mean retention decreased to less than 5 N for Groups 2 and 3 (**Fig. 6**).

Overall, the interaction between the offset parameter and the polishing method in the GLM showed that the offset parameter had a significant effect after artificial aging, whereas the polishing method significantly affected the retention forces before artificial aging. In particular, the results of the GLM models were:

- Dry/wet conditions before aging:
  offset parameter: $F = 4.46, P = 0.04$ / $F = 0.58, P = 0.45$;
  polishing method: $F = 3.46, P = 0.07$ / $F = 8.13, P = 0.01$
- Dry/wet conditions after artificial aging:
  offset parameter: $F = 16.01, P < 0.01$ / $F = 6.28, P = 0.02$;
  polishing method: $F = 1.59, P = 0.21$ / $F = 1.48, P = 0.23$

The difference between dry and wet conditions was statistically significant only for Groups 2 and 3 before aging (Group 2: $P = 0.022$, Group 3: $P = 0.001$) After aging, surface conditioning had no significant effect ($P > 0.125$ for all Wilcoxon tests) on the retention forces.

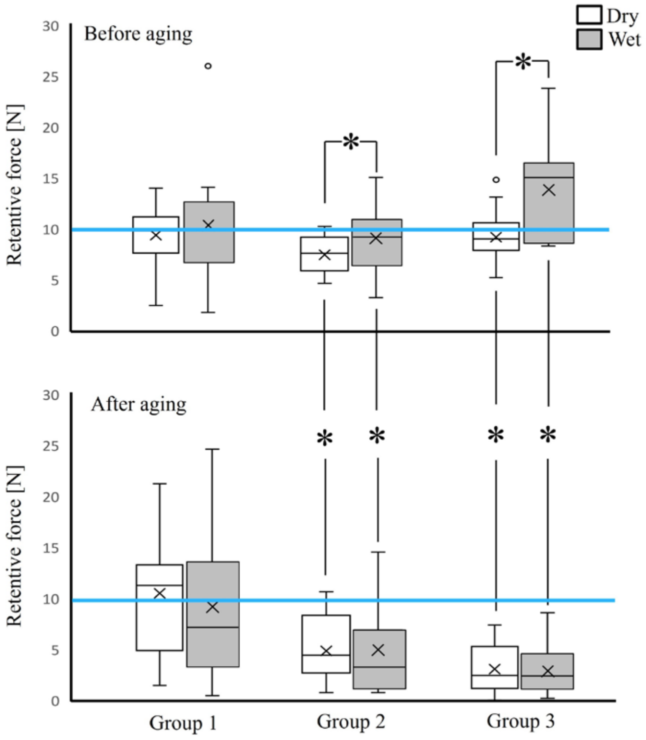

Fig. 6. Differences of retentive force before and after aging. The blue line indicates the targeted initial retentive force of double crown. Asterixes show significant differences identified with Wilcoxon tests

The above-described drop in retention for Groups 2 and 3 (both groups have an offset parameter of -10 µm) was highly significant ($P < 0.003$ for all Wilcoxon tests), whereas no aging effect was observed for Group 1 (dry surface condition: $P = 0.363$, wet surface condition: $P = 0.552$) (**Fig. 6**).

Figure 7 shows SEM images of the inner surface of the secondary crown after milling and after adjustment using each of the two polishing methods. Comparing the surface morphologies, clear differences were observed between the two polishing methods. While polishing with diamond paste generated mostly abraded surfaces for both the composite and glass fiber areas, the use of silicon points led to dominantly fractured glass fiber ends. **Figure 8** shows the inner surface of the crowns of group 1 after aging. Abrasion marks running roughly parallel to the path of the insertion/removal of the crown could be identified, as well as local roughening of the surface, due to small abfractions.

4. Discussion

The double crowns used in this study were fabricated using CAD/CAM technology. The zirconia selected for the primary crown is a suitable material from the perspective of the long-term prognosis for primary crowns that are attached to abutment teeth because of their high strength, high biocompatibility, and low adhesion to plaque. Schwindling et al. reported that the retention behavior of zirconia primary and secondary crowns is stable if they have been fabricated with suitable milling and sintering parameters [16]. Turp

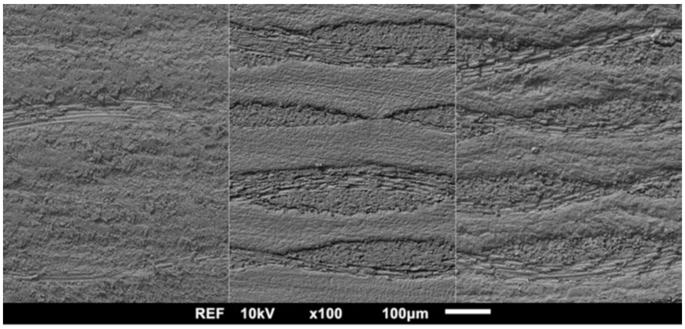

Fig. 7. Images showing crown surfaces with glass fiber bundles oriented parallel and perpendicular to the surface. Left image: after milling Center image: after milling and polishing with diamond paste Right image: after milling and polishing with silicon points.

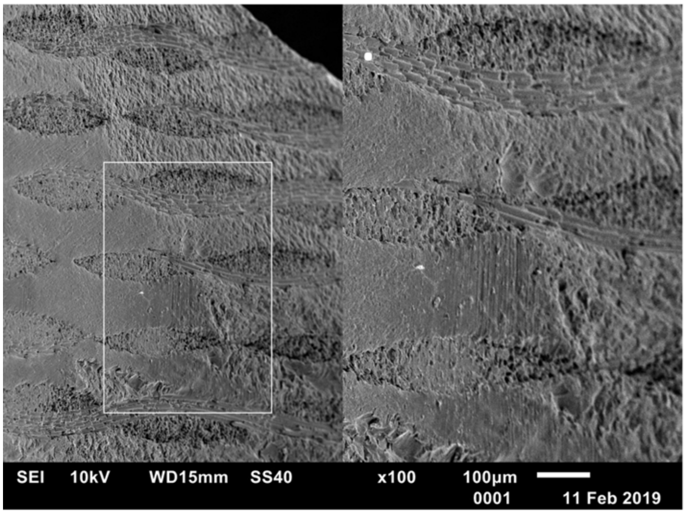

Fig. 8. Low-magnification SEM image (left, 100×) of inner crown surface. High-magnification SEM image (right, 200×) of the boxed region of left image, showing the inner crown surface that suffered from wear due to artificial aging.

et al. performed repeated insertion/removal tests with double crown combinations of zirconia primary/electroformed gold secondary and zirconia primary/non-metal secondary crowns, and they found almost no difference in retentive force and almost no abrasion of the zirconia primary crown [17]. Schubert et al. reported that a stable retentive force was retained with a zirconia primary crown and polyetheretherketone secondary crown in a repeated insertion/removal test equivalent to 10 years of wear [25]. However, poly (ether ether ketone) (PEEK) has a very inert surface that leads to poor bonding with dental materials [26].

FRC was selected as the material for the secondary crown. In the medical field, FRC is used in flexible regions, such as ligaments, intervertebral disks, artificial tendons, and hip joint stems [27]. In the field of dentistry, FRC is used mainly for fixed prostheses, such as bridges and implant superstructures [23,24]. As it already has a range of applications, the use of FRC in removable prostheses is a possibility. Fitting the FRC secondary crown to the primary crown is easier than that of zirconia secondary crown because the FRC does not require a sintering process and there is no error in the sintering process. To date, secondary crowns fabricated from FRC have been used in clinical studies, 3D finite element analyses, and breaking tests [22,28], but there have been no studies in which retentive force tests and repeated insertion/removal tests were performed. The adjustment parameters during milling of the secondary crown were determined through test processing in advance. We confirmed that the production of telescope crowns using CAD/CAM technology is significantly influenced by the human intervention of setting the milling parameters. Two methods were used to correct the conformity of the secondary crown to the primary crown. The first was to make the secondary crown with a tight fit and adjust the retentive force by adjusting the inner surface of the secondary crown. The second method was to produce a correct fit through milling alone. The time needed for adjustment of the retentive force tended to be longer for Group 1 than for Groups 2 or 3 (Group 1: 13.1±3.3 min/crown; Group 2: 7.9±6.2 min/crown; and Group 3: 8.9±5.0 min/crown). The retention of the samples was adjusted by a dentist who participated in the study. The two polishing methods were polishing with a paste for use on hard resins and polishing with silicon points for use on composite resins. In a preliminary study, we attempted polishing with various polishing points and pastes and selected the diamond paste that resulted in the smoothest polish. In addition, we selected the silicon points recommended by the manufacturer. Diamond polishing led to the smoothest surfaces, and the glass fiber tips did not fracture but were flattened. By contrast, silicon points were less sensitive, leading to fractures of the glass fiber tips and hence a somewhat rougher surface.

We loaded different fitting forces in the first phase of the retention test. Fernandes et al. reported that the chewing force of individuals using removable partial dentures retained by double crowns could change between 28 N and 252 N [29]. Therefore, in this experiment, the preload was within the range of the masticatory forces. The FRC material used for CAM machining has no water saturation after manufacturing. This changes after an FRC crown is placed in a patient´s mouth. Owing to this water uptake, slight dimensional changes may occur. To include this possible effect, the secondary crowns were stored in distilled water at 37 °C for 1 week before the retentive force measurements. Wet and dry conditions during retention testing refer to the interface between the primary and secondary crowns. In the former case, the interface surfaces were air-dried before the tests, and in the latter case, surfaces were wetted (similar to a saliva coating) such that small gaps between the primary and secondary crowns were filled with fluid during the fitting procedure. Under dry conditions, all groups were able to achieve an initial retentive force of 3.57 N, which is considered necessary for double crowns [30]. However, there were large variations in the retention in each group. It is considered that this was influenced by the differences in height of the abutment teeth due to the use of various tooth types in this experiment [31,32]. Under wet conditions, the initial retentive force was statistically significantly greater in Group 3 than in Group 2, suggesting the possibility that the effects of bonding through water pressure were greater in Group 3. The same phenomenon has been observed for Galvano telescopic crowns [33].

Regarding the setting of the chewing simulator, the essential part was the maximum fitting force. We chose a force magnitude associated with manual insertion by the patient (approximately 50 N, which is a rather high manual fitting force). The change in retentive force following artificial aging decreased in Groups 2 and 3 but showed a tendency to increase in Group 1. Behr et al. reported that secondary crowns ill-fitted onto primary crowns led to both decreases and increases in retentive force, which are opposite results [34]. In this study, the same tendency was found under both dry and wet conditions, suggesting that the effects of bonding through water pressure were not manifested in the wet condition after artificial aging. After aging, the small gaps between the primary and secondary crowns were not sealed, thus reducing the effect of hydraulic adhesion.

Under the conditions in this study, the median values and the interquartile ranges of the changes in retentive force suggest that milling FRC secondary crowns according to both the milling parameters used for Group 2 and polishing of the inner surface using diamond paste produce few long-term changes, which makes changes in retentive force easy to predict. This means that minimal adjustments, such as those in Group 2, can lead to the production of a double crown. It was suggested that changing the polishing method and milling offset value has the potential to reduce the manual adjustment time.

The FRC used in this study was comprised of numerous layers of glass fiber and resin interlaced in multiple directions. Therefore, it is extremely flexible and durable. FRC is a non-metallic, hypoallergenic, biocompatible, and esthetic material. The advantages of combining zirconia primary crowns and FRC secondary crowns and CAD/CAM-supported manufacturing might, therefore, lead to new options in double crowns with good biological and mechanical properties and might reduce fabrication costs and time. From the perspective of the material characteristics and regarding the combination of a zirconia primary crown and a FRC secondary crown used in this study, the FRC secondary crown was expected to wear away as a result of repeated insertion/removal. Ten thousand insertion/removal cycles correspond to a clinical service time of 10 years with three insertions per day. Abrasion marks on the resin surface due to repeated insertion/removal of the primary and secondary crowns were observed, and wear to the inner surface of the secondary crown led to a poor fit over long-term use. However, the conformity may be improved by adding resin to repair the worn inner surface of the secondary crown. This needs to be confirmed through further studies. A limitation of this study was that it did not make a comparison with the telescopic crown made by conventional casting. In addition, as only one convergence angle was used for the primary crown, further study is required to investigate other angles.

5. Conclusion

In this study, telescopic crowns comprising of a combination of zirconia primary crowns and FRC secondary crowns exhibited an adequate initial retentive force. The results also suggest that adjustment of the milling parameters for the secondary crown and polishing after milling can greatly affect the manual adjustment time after milling and the long-term clinical prognosis of the double crown.

Acknowledgements

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Conflicts of interest

This study was supported by Shofu, Inc. (Kyoto, Japan), who supplied FRC discs.

There is no conflict of interest.

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