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Tensile Bond Strength, Fit Accuracy and Failure Types of Zirconia and Cast Gold Root Copings for Overdentures

ABSTRACT

Aim: To compare the tensile strength, dislodgement forces, marginal gap and failure types between digitally fabricated zirconia root copings and conventionally manufactured cast gold root copings. *Methods:* Extracted human teeth (N=30) were prepared for the root copings and randomly divided into 2 groups: (1) zirconia root copings (ZC) and gold root copings (GC). The specimens were tested for tensile bond strength and dislodgement forces in a universal testing machine and the types of the coping failures modes were analyzed. In addition, the marginal gap was measured. Data were analyzed using one-way ANOVA and Pearson correlation test. *Results:* Mean tensile bond strength in the total horizontal adhesive area for ZC group was 7.5 ± 2.8 MPa and for GC group 10.5 ± 4.8 MPa ($p > 0.05$). The mean dislodgement forces for the ZC and GC groups were 242 ± 107 N and 311 ± 118 N, respectively and with no significant differences between the groups ($p = 0.12$). The mean vertical marginal gap in the ZC group amounted to 27 ± 11.05 μ m, while in the GC group it was 35.33 ± 10.49 μ m, showing no statistically significant difference between the two groups ($p = 0.058$). Mixed failure modes were more common (93%) in both groups. *Conclusions:* In terms of all tested parameters, the zirconia root copings were comparable to the gold copings.

INTRODUCTION

Tooth-supported overdenture treatment modality with significant clinical and patient-related advantages is a predictable option for the partially edentulous patients¹. The integration of root copings into the remaining teeth structure can significantly enhance overdenture stability, retention, masticatory function and the preservation of the alveolar bone¹. However, it is important to note that root copings may be susceptible to complications including decementation, loss of retention, secondary caries, root fracture and need for repair or retreatment. These complications can often be attributed to various factors such as design characteristics, tooth preparation design, material physical properties, marginal fit, and bond strength to the abutment teeth²⁻⁹.

Gold alloy remains the gold standard material for casting root copings due to its proven biocompatibility and clinical efficacy^{10,11}. Before the establishment of digital technologies, resin composite root copings were alternative to gold root copings^{12,13}. However, the fabrication of composite root copings

required specialized knowledge of the dental technicians and was just as time-consuming as the process of making gold root copings. Furthermore, the design of composite root copings tended to be bulkier compared to cast gold root copings. As a result, they required more interdental and occlusal space, which limited their applicability in certain clinical situations.

Recent developments in digital technologies have opened up the opportunity of computer-aided design and manufacturing (CAD-CAM) of zirconia root copings, aiming to streamline clinical and lab workflow. Currently, CAD-CAM zirconia-based ceramic restorations are favored for their reproducibility, high aesthetic appeal, rapid fabrication times, high dimensional precision and minimized technical errors¹⁴⁻¹⁶. Among CAD-CAM restorations, zirconia root copings stand out not only for their efficiency but also for their cost-effectiveness. They are slightly cheaper than gold root copings and require a less invasive tooth preparation compared to the latter, as the root canal does not need to be prepared for post fixation.

The Y-TZP (yttria-stabilized tetragonal zirconia polycrystal) is the most widely used type of CAD-CAM zirconia-based ceramics due to its high fracture toughness, flexural strength, wear resistance and reduced susceptibility to bacterial plaque¹⁷⁻²². In this context, the 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) has established itself as the primary ceramic, particularly in clinical applications where translucency is not the primary concern, such as frameworks in porcelain-veneered crowns and fixed dental prostheses (FDPs) in posterior and anterior regions²³. Both the advantageous mechanical properties of yttrium-stabilized zirconium dioxide and advancements in adhesion promoters, which involve adequate preparation of dental tissue and restoration, along with the use of MDP-containing primers and cements, enable the use of this material without needing to consider macro-mechanical principles. From this perspective, yttrium-stabilized zirconium dioxide root copings could become an alternative to conventional gold copings^{19,24,25}. However, to the best of our knowledge, there are currently no data on the use of Y-TZP for root copings and no studies compared zirconia and cast gold root copings for their retention or adhesion.

Therefore, the aim of the present study was to compare the tensile strength, marginal gap and failure modes between digitally fabricated zirconia root copings and conventionally manufactured cast gold root copings. The null hypothesis tested was that there would be no difference between two types of reconstructions in terms of tensile strength, marginal fit and failure modes.

MATERIAL AND METHODS

SPECIMEN PREPARATION

Extracted human teeth (maxillary central incisors, canines, premolars and mandibular canines and premolars) (N = 30), due to periodontal reasons, were kept in distilled water until the experiment at 4°C and during experiments at 23°C. The

teeth were selected that provided sufficient dental hard tissue for the preparation of inlays with a depth of at least 1.5 mm and a diameter of at least 2.5 mm, along with a remaining dentin wall of at least 1 mm after preparation on the periphery. The reasons for the extraction of the teeth used in this study were unrelated to the study as we have focused only on the dimensions of the adhesive area of prepared teeth. Written informed consent for the research purpose of the extracted teeth was obtained by all donors prior to extraction according to the directives set by the National Federal Council. Ethical guidelines were strictly followed, and irreversible anonymization was performed in accordance with State and Federal Law²⁶. After removal of the pulp, the intraradicular canals were cleaned and prepared with ProTaper Next endodontic rotary files (Dentsply Sirona, USA). The root canals were not filled in order to avoid possible contamination of the intraradicular dentin with subsequent root canal filling materials. The coronal section of the teeth, positioned 1 mm below the cement-enamel junction (CEJ), were removed under water cooling, using a diamond bur (Type 859, Intensiv SA, Switzerland). Subsequently, the occlusal surfaces and inlays of the shortened teeth were prepared using diamond burs (Type 368, 845, Intensiv SA, Switzerland).

All specimens were then randomly divided into 2 groups: (1) zirconia root copings (ZC) and (2) gold root copings (GC).

Group ZC: The teeth were scanned with laboratory scanner (3Shape D1000) and the zirconia root copings were designed (3Shape Software) and manufactured using the high strength zirconia material (Katana Zirconia HTML discs, Kuraray, Noritake Dental Inc., Japan). This material belongs to the second generation of 3 mol% yttria-stabilized zirconia, characterized by superior flexural strength (1000-1500 MPa) and high fracture toughness (3.5-4.5 MPa)¹⁷. The thickness of all zirconia root copings was 1.5 mm at the marginal area, which is above the minimum layer thickness of 0.5 mm, considered sufficient to withstand chewing forces^{27,28}. The ball attachment was designed as a retention element.

The intaglio surfaces of the zirconia root copings were airborne-particle abraded (Basic quattro IS, fine air-abrasion unit, Renfert GmbH, Hilzingen, Germany) (50 µm Al₂O₃, for a duration of 10 s, at 4 bar pressure, and a distance of 10 mm). These surfaces were then conditioned with a silica coating (CoJet System, 3M ESPE, St. Paul, USA), cleaned in the ultrasonic bath and coated with an 10-methacryloyloxydecyl dihydrogenphosphate (MDP) monomer-containing primer (Clearfil Ceramic Primer, Kuraray Noritake Dental Inc., Japan) before being cemented with MDP-containing adhesive resin cement (Panavia 21, Kuraray Noritake Dental Inc, Japan.) in accordance with the prescribed protocol and the recommendations of numerous studies²⁹⁻³².

Group GC: The root canals of the teeth were prepared and mechanically enlarged so that 7 mm long intraradicular posts (Moser root canal posts, Cendres+Métaux SA, Biel, Switzerland) could be inserted into the prepared root canals. The diameter of the inserted posts varied and depended on the diameter of

the respective root canals. After positioning of the posts in the prepared root canals, the impressions were made using polyether impression material (Permadyne™, 3M ESPE AG, Landsberg am Lech, Germany), and stone casts (super-hard stone type 4, Marmorock® Saphir, Siladent Dr. Böhme & Schöps GmbH), Goslar, Germany were subsequently obtained. The gold root copings were fabricated using the lost-wax technique and cast in a high-gold type IV alloy (Protor 3, Cendrex&Métaux, Biel, Switzerland). Retention elements in the form of ball attachments were soldered to the blanks, and the root copings were then finished and polished up to 0.3 mm material thickness at the marginal area.

The cementation surfaces were airborne-particle abraded (Basic quattro IS, fine sandblasting unit, Renfert GmbH, Hilzingen, Germany) (50 µm Al₂O₃, for a duration of 10 s, at 4 bar pressure, and a distance of 10 mm). The gold root copings were cleaned in the same way as the zirconia root copings. They were coated with metal primer (Alloy primer, Kuraray Noritake Dental Inc, Japan.) and cemented using MDP-containing adhesive resin cement (Panavia 21) in accordance with the prescribed protocol and recommendation of other investigators^{33,34}.

All specimens from both groups were kept in distilled water until the experiment at 4° and during experiments at 23°, prior to the mechanical tests.

SURFACE AREA MEASUREMENT

Digital models of all teeth were obtained after root canal preparation using a laboratory scanner (3Shape D1000). Data were stored as stereolithography mesh objects and imported into a CAD software (Rhinoceros 3D V. 7.0, McNeel Inc., Seattle WA, USA). Vertical and horizontal surface areas were calculated from the mesh objects according to their angle with the horizontal plane. Meshes that formed an angle between 80° and 120° with the horizontal plane were considered as vertical surface and the remaining as horizontal surface.

MECHANICAL TESTS AND FAILURE MODES ANALYSIS

The specimens were tested for tensile strength and dislodgement forces of the root copings in a Universal Testing Machine (Zwick/Roell Z010, Zwick GmbH, Ulm, Germany). In order to ensure reproducibility, a custom-made jig was constructed for the purpose of securely mounting the specimens in the device. Subsequently, each specimen was subjected to tension by being pulled from the attachment ball until either the copings fractured or debonded, at a cross head speed of 1 mm/min. During these tests, both tensile strength values, dislodgement forces were measured. After the tests failure modes were classified¹³.

The tensile bond strength (MPa) in the tensile test was measured on the external horizontal adhesive area (areas A) and on the total horizontal adhesive area (areas A+C) in Figure 1a and Figure 1b. The dislodgement forces were measured in N.

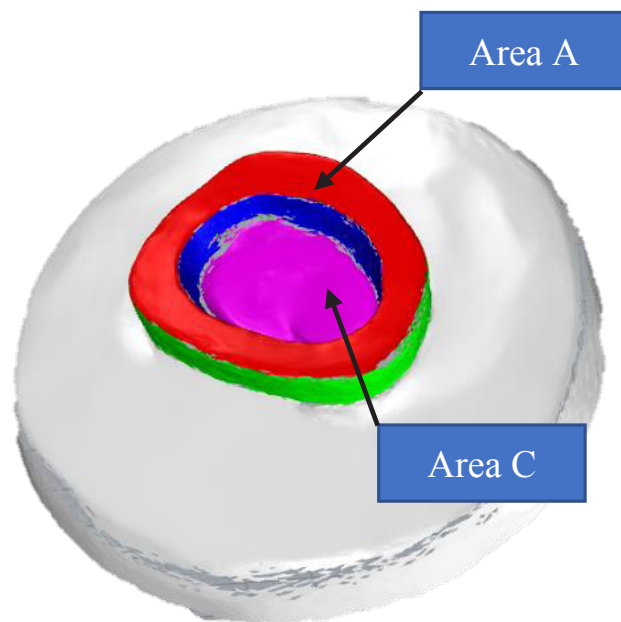


Figure 1a: Scan view of external horizontal adhesive area (area A) and total horizontal adhesive area (areas A+C) considered during calculation of adhesive surface and measurement of ultimate stress measurements.

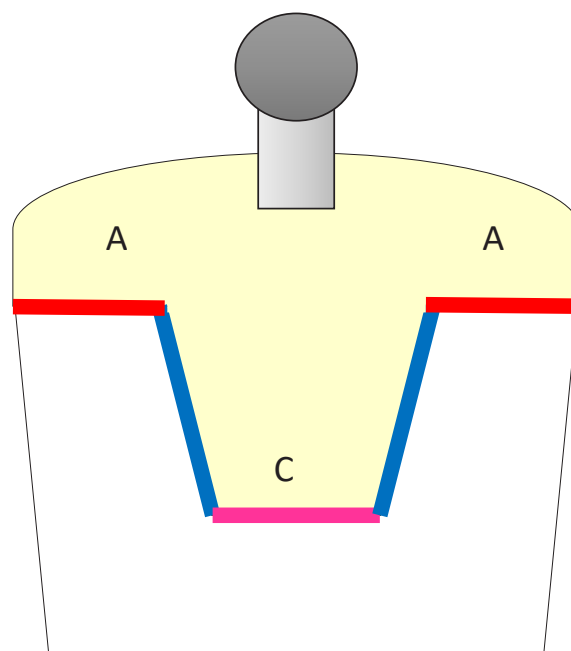


Figure 1b: Schematic of definition of external horizontal adhesive area (area A) and total horizontal adhesive area (areas A + C) considered during adhesive surface calculation and ultimate stress measurements.

All coping surfaces were further analyzed and failure modes were scored as follows: A: Adhesive, coping debonded adhesively from the tooth with no remnants of cement/adhesive resin on the tooth surface; M: Mixed, partial remnants of cement/adhesive resin on the coping; C: Cohesive, coping material remained completely on the tooth surface¹³.

VERTICAL MARGINAL GAP MEASUREMENT

For each specimen, the vertical marginal gap was measured at 4 quadrants, with three measurement points in each quadrant, using a digital microscope (Keyence VHX 200) at a magnification of x200.

STATISTICAL ANALYSIS

Descriptive statistics was performed on all observed parameters. Shapiro-Wilk tests were used to assess the normal distribution of the data, and in the case of non-normality, a logarithmic data transformation was applied to the variable, or non-parametric tests were used. Accordingly, either a univariate analysis of variance (one-way ANOVA) or Mann-Whitney-U-Test was utilized to compare tensile bond strength, dislodgement forces and gap size between the two groups. In order to determine the correlation between tensile bond strength acting on the external horizontal area surface and marginal gap the Pearson's correlation test was conducted. Data analysis was performed using two statistical software packages (SPSS Software V.29 Chicago, IL, USA and Graphpad Software Inc.). The significance level was set at $\alpha = 0.05$.

RESULTS

Twenty-nine out of 30 specimens were analysed for gap measurements, while for stress analyses 28 specimens were available. Samples were excluded due to an abnormal gap ($n=1$, GC) and tensile pre-test failure ($n=2$; ZC=1, GC=1).

The mean total and external horizontal adhesive areas for the ZC and GC groups were almost identical ZC: $31.43 \pm 5.66 \text{ mm}^2$; $20.54 \pm 4.41 \text{ mm}^2$ and GC: $30.54 \pm 5.27 \text{ mm}^2$; $19.91 \pm 3.66 \text{ mm}^2$, respectively ($p = 0.746$; $p = 0.324$) (Table 1) (Figure 1a-b).

In the external horizontal area, the mean tensile bond strength was significantly higher for the GC group ($16.21 \pm 7.25 \text{ MPa}$) compared to that of the ZC group ($11.55 \pm 4.07 \text{ MPa}$) ($p=0.046$) (Table 1) (Figure 2).

When comparing the tensile bond strength on the total horizontal adhesive area (areas A + C; Figure 1a-b), no significant differences were found between the groups ($p = 0.085$) (Table 1) (Figure 3).

The mean dislodgement forces for the ZC and GC groups were $242 \pm 107 \text{ N}$ and $311 \pm 118 \text{ N}$, respectively, without statistically significant difference ($p = 0.12$) (Figure 4).

The overall incidence of mixed coping failures (Type M) amounted to 93% in both groups. In the remaining 7% of cases, the failure mode differed. While in the GC group, one tooth fractured, in the ZC group one zirconia root coping fractured. In both cases, the copings did not detach from the tooth.

As for mean vertical gap, there was trend towards to a lower gap in the ZC group ($27.40 \pm 11.05 \mu\text{m}$) compared to GC group ($35.33 \pm 10.49 \mu\text{m}$) (intergroup $p=0.058$) (Table 2) (Figure 5).

Regarding the correlation analysis of marginal gap and mean ultimate tensile strength on the external horizontal adhesive area differences, the Pearson's correlation test revealed a negligible negative correlation in the ZC group ($r=-0.10388$, $p = 0.724$) (Figure 6) and low negative correlation in the GC group ($r=-0.307$, $p = 0.307$) (Figure 7).

Table 1. Adhesive surface measured in mm^2 (areas A and C) and tensile bond strength measured in MPa on the external horizontal adhesive area (area A) and on the total horizontal adhesive area (areas A + C) observed in each experimental group.

Group		Horizontal area A [mm^2]	Intergroup p-value	Horizontal area C [mm^2]	Intergroup p-value	Tensile bond strength A [MPa]	Intergroup p-value	Tensile bond strength A + C [MPa]	Intergroup P-value
Zirconia (n=14)	Mean	20.54		10.88		11.55		7.58	
	SD	4.41		1.96		4.07		2.86	
	Median	20.73		10.51		11.49		7.46	
	Q1	16.04		9.17		6.09		3.72	
	Q3	25.17	0.324	13.01	0.929	19.20	0.045	12.86	0.085
Gold (n=14)	Mean	19.91		10.63		16.21		10.56	
	SD	3.66		1.94		7.25		4.85	
	Median	18.88		10.29		16.78		10.61	
	Q1	13.78		8.10		7.89		5.11	
	Q3	25.83		13.82		35.10		23.51	

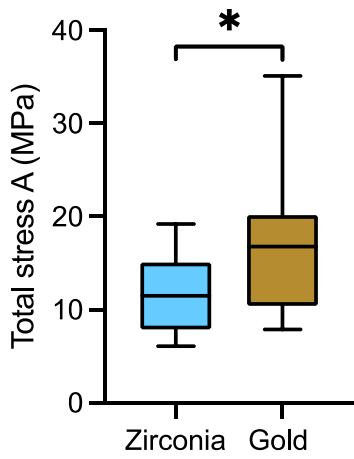


Figure 2: Tensile bond strength of zirconia and gold copings measured on the external horizontal adhesive area (area A). *indicates $p=0.045$.

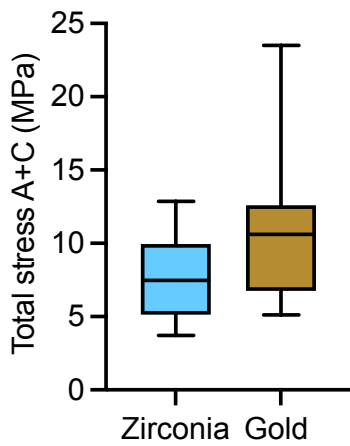


Figure 3: Tensile bond strength of zirconia and gold copings measured on the total horizontal adhesive area (areas A + C).

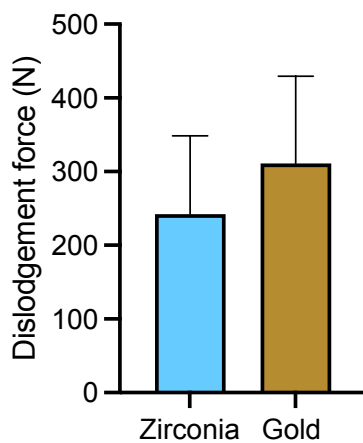


Figure 4: Mean dislodgement forces (N) of zirconia and gold copings. Error lines indicate SD.

Table 2. Mean (SD) and median (Q1, Q3) values of marginal gaps in μm observed in each experimental group (n=29).

Group		Gap	Intergroup p value
Zirconia (n=15)	Mean	27.40	0.0580
	SD	11.05	
	Median	25.00	
	Q1	19.10	
Gold (n=14)	Mean	35.33	
	SD	10.49	
	Median	32.38	
	Q1	28.17	
	Q3	43.44	

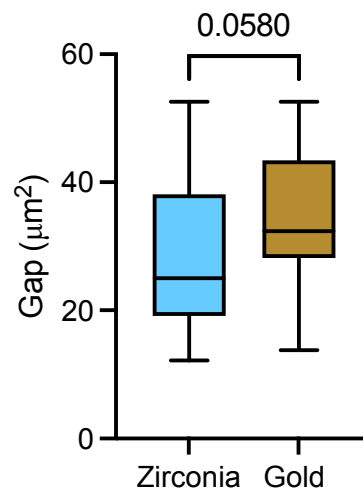


Figure 5: Gap values of zirconia and gold copings.

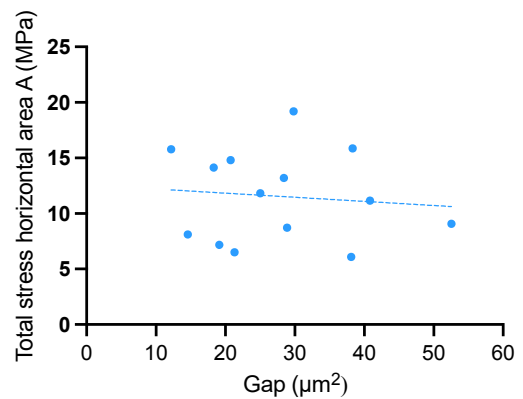


Figure 6: Scatter plot of the correlation between marginal gap and mean tensile bond strength on the external horizontal adhesive area differences for ZC group (Pearson`s correlation coefficient $r=-0.10$; $p=0.724$).

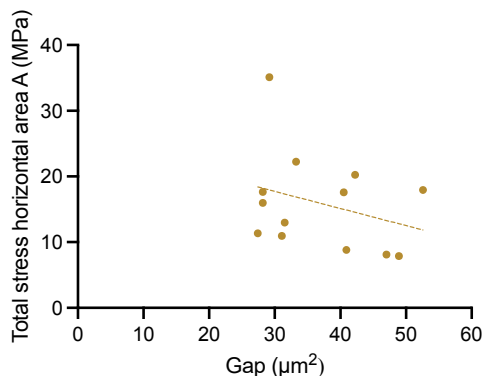


Figure 7: Scatter plot of the correlation between marginal gap and mean tensile bond strength on the external horizontal adhesive area differences for GC group (Pearson correlation coefficient $r=-0.307$; p -value = 0.307).

DISCUSSION

The present study comparing zirconia and gold root copings in terms of tensile bond strength, dislodgement forces, failure modes and vertical marginal gap predominantly revealed similar tensile bond strength and dislodgement forces values between both groups with a trend toward lower gap in the ZC group, being not significant. Also, comparable type of failures modes were observed in both groups. Consequently, the null hypothesis that there would be no difference between two types of reconstructions in terms of tensile bond strength, dislodgement forces, failure modes and vertical marginal gap was accepted.

The zirconia root copings were cemented after physico-chemical activation of the ceramic surface and using an MDP-containing primer and cement, which led to a significant improvement of bond strength, as shown by numerous studies^{25, 29-32}. The intaglio surface of the metal copings was airborne-particle abraded and then coated with the alloy primer to improve the tensile strength and bond ability of the cement to the metal restoration, in accordance with the literature³³⁻³⁷. The mean tensile bond strength for the total horizontal adhesive area of the zirconia group was 7.58 MPa and did not differ statistically significantly from the gold group. This value is comparable to the results by a previous report in which the removal stress values for zirconium crowns cemented with different cements were between 5.0 and 6.1 MPa³⁸. Furthermore, the mean tensile strength value of 10.56 MPa in the gold group falls within the range of the dislodgement stress observed for gold copings cemented with various cements³⁹.

In terms of mean dislodgement forces, there was no significant difference between the two groups. Moreover, in both groups, the mean dislodgement forces of 242 ± 107 N (ZC group) and 311 ± 118 N (GC group) exceeded the clinically expected 40 N and could thus be considered clinically acceptable⁴⁰.

In the current study, the mean marginal vertical gap for gold root copings was found to be 35.33 ± 10.49 μm , which is comparable with other studies⁴¹⁻⁴³. The mean marginal vertical gap of 27.40 ± 11.05 μm obtained in this study for zirconia root copings appears to compare well within the clinical acceptability threshold of 120 μm ⁴⁴. The marginal gap revealed in the present study generally was smaller than that found in other studies on the marginal fit of zirconia crowns fabricated with digital methods^{45,46}. This might be explained by the fact that in the present study, the prepared teeth were direct digitalized using a laboratory scanner and the laboratory scanners are known to have a better degree of accuracy⁴⁷. Nevertheless, the marginal gap of both groups fell within clinically acceptable limits of marginal opening.

The present study found a negligible negative correlation for the zirconia root copings, and a low negative correlation for the gold root copings between the marginal gap and the mean ultimate tensile strength. It has been suggested that the tensile bond strength is influenced by numerous factors including preparation form, surface, length and diameter of the root canal posts, cementation protocol, and reconstruction material⁴⁸⁻⁵³.

When categorizing the types of failures modes, an interesting finding was the frequent presence of cement on both the intaglio surface of the root copings and the tooth surface in both groups. This observation correlates with the similar tensile strength values in both groups and suggests a comparable bond between the luting cement and the two materials. The occurrence of a root fracture in one of the gold copings indicates a weakening of the tooth root, which can occur during the preparation of the root canal for the post of the root coping. Clinically, this type of failure frequently manifests as a root fracture preceding the debonding of the gold root coping. The fracture of one of the zirconia root copings before debonding could be explained by a surface defect that can occur during the milling of zirconia and can have a negative impact on fracture strength⁵⁴.

The different geometry of the tooth preparations, the shape of the two types of root copings, and the various cementation protocols make it difficult to directly compare the root copings. This also makes it challenging to compare the results of this study with those of other studies, as, to the authors' knowledge, there are no studies on zirconia root copings. One limitation is the fabrication of the zirconia root copings based on digital impressions using a laboratory scanner, which does not correspond to clinical conditions.

The use of new materials and digital technologies in removable prosthodontics deserves further research attention to develop new prosthetic workflows that are currently lacking. The present study showed that zirconia root copings are comparable to gold copings in terms of tensile bond strength, dislodgement forces, and failures modes, with no significant difference. However, compared to gold copings, the fabrication of ceramic copings is more expeditious, exhibits better

reproducibility, higher dimensional precision, and improved aesthetics. Additionally, it minimizes technical errors and allows for a more efficient workflow in treatments with overdentures. This suggests broader clinical use for zirconia and that digitally manufactured zirconia root copings for the overdentures might be a promising alternative to the conventional cast gold ones. Future clinical studies are needed to validate these findings and to investigate tooth-supported overdentures on zirconia root copings with regard to biological and technical complications.

CONCLUSIONS

From this study, the following could be concluded:

1. Zirconia and gold root copings presented similar tensile bond strength, dislodgement forces and marginal gap.
2. Failure modes were predominantly mixed where partial remnants of cement/adhesive resin were evident on the copings.
3. Negligible negative correlation was found between marginal gap and mean ultimate tensile strength in zirconia root copings and low negative correlation in the gold coping group.

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