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Original article

Influence of wall thickness on the fracture resistance of hollow zirconia artificial teeth fabricated by 3D zirconia printing

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Abstract

Purpose: To determine the effect of wall thickness on the fracture load of hollow-structured zirconia teeth fabricated using 3D printing.

Methods: The geometry of an artificial ceramic tooth (mandibular right first molar) was copied and modified. The final test group design yielded wall thicknesses of 0.30, 0.50, 0.75, and 1.00 mm. Twenty zirconia specimens from each group were fabricated using a 3D printer. Artificial teeth were divided into subgroups of teeth that remained hollow (hollow teeth) or were filled with resin (filled teeth). Fracture load tests were performed, and each artificial tooth was examined using a digital microscope. Analysis of variance was used to compare the fracture resistance of the artificial zirconia teeth among the conditions, followed by pairwise Tukey's tests. T-tests were used to compare the fracture resistance between the hollow and filled teeth within the test groups.

Results: The fracture resistance of artificial zirconia teeth decreased significantly ($P < 0.001$) with decreasing wall thickness. The mean fracture load reached ≥500 N for wall thicknesses of 0.75 mm and 1.00 mm. Resin filling of crowns significantly improved the fracture load of very thin walls. Microscopy revealed that most occlusal surfaces of the hollow teeth were completely fractured, whereas all the fracture surfaces of the filled teeth were incompletely fractured.

Conclusions: Artificial zirconia teeth offer sufficient fracture resistance for clinical use when the wall thickness is ≥0.75 mm, regardless of the presence of resin filling.

Keywords: Removable partial dentures, Zirconia artificial tooth, CAD-CAM, 3D printer, Fracture resistance

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1. Introduction

Resin materials, such as acrylic and composite resins, are widely used for artificial teeth because of their ease of occlusal adjustment and compatibility with computer-aided design/computer-aided manufacturing (CAD-CAM) technology, which allows for milling or 3D printing[1–4]. However, the resin has disadvantages such as water absorbency, discoloration, plaque adhesion, and potential occlusal wear[5–18]. Alternatives such as classical dental ceramics and alloys offer higher mechanical strength, no water absorption, and less plaque adhesion[3,7–16,19–22]. However, classical dental ceramics are brittle and require surface conditioning and primers to bond with the denture base resin, necessitating mechanical retention elements such as holes or pins, which may not always be feasible in cases of infraocclusion[5,14,18,23–27]. Alloy-based artificial teeth, although strong, have poor esthetics and potential risks such as metal allergies[15,17,28,29]. Thus, each material has its advantages and limitations (**Table 1**).

Given these drawbacks, the development of alternative materials is crucial. This study focused on zirconia as a promising alternative for creating artificial teeth. Zirconia has gained attention in prosthodontics due to its high strength and excellent esthetics, enabled by advances in CAD-CAM technology[9–12,15,16,20,22,30–38]. Zirconia crowns and other prostheses are typically fabricated using milling machines, significantly improving fabrication efficiency[39,40]. However, milling technologies have limitations, including restric-

WHAT IS ALREADY KNOWN ABOUT THE TOPIC?

» *Existing materials for artificial teeth have drawbacks such as water absorption, brittleness, and poor esthetics. Zirconia has great potential as an alternative. Although zirconia has excellent properties, the effects of wall thickness and resin filling on the fracture resistance of 3D-printed hollow-structured artificial zirconia teeth remain unclear.*

WHAT THIS STUDY ADDS?

» *Wall thickness of 3D-printed, hollow-structured zirconia artificial teeth significantly impacts fracture resistance. Resin inside the hollow structure affects resistance when wall thickness is ≤0.30 mm. Clinically, zirconia teeth with a wall thickness of ≥0.75 mm are recommended for sufficient durability.*

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Table 1. Characteristics of each material

	Resin	Porcelain	Metal	Zirconia
Wear resistance	Poor [8–11]	Very Good [8–11]	Very Good [9]	Excellent [9–11]
Hardness	Fair [12,13]	Very Good [12,13,20]	Good [13]	Excellent [12,20]
Impact resistance	Good [14]	Poor [14,24]	Excellent [14]	Fair [24]
Aesthetics	Good [15,16]	Excellent [15,16,21,22]	Poor [15]	Very Good [15,16,22]
Allergic risk	Moderate [17]	Low [29]	High [17,28,29]	Low [28,29]
Adhesion to resin	Excellent [18]	Poor [18,26,27]	Poor [18,26]	Poor [25,27]

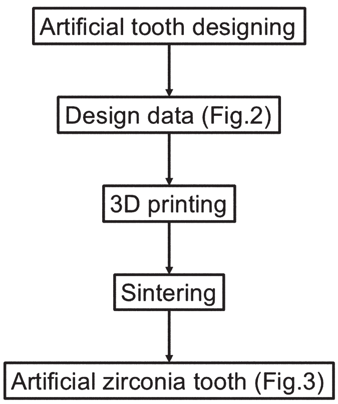

Fig. 1. Diagram of the production procedure

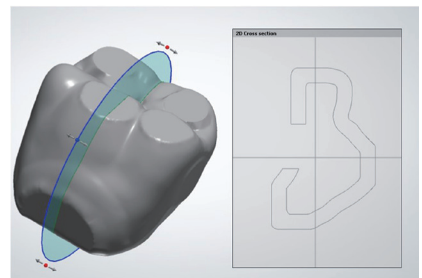

Fig. 2. Images of the tooth design. Left: outer geometry of the tooth; right: sliced image of the tooth.

tions on the shape and motion range of milling burs and significant material waste, such as debris and surplus parts of the blank after fabrication[39–42]. In contrast, 3D printers can be used to create various fabrications. Various studies have been conducted in prosthodontics using 3D printers[43–45]. Unlike milling, 3D printing allows the creation of internal structures and complex geometries without the restrictions of milling while reducing material waste[39,46]. The recent use of zirconia in 3D printing further enhances its advantages over milling[42]. This study investigated the fabrication of artificial zirconia teeth using 3D printers.

However, several issues must be addressed when fabricating artificial zirconia teeth. Zirconia does not chemically bond to the denture base resin and requires pretreatment with sandblasting and 10-methacryloxydecyl dihydrogen phosphate, which are essential for bonding[47,48]. Mechanical interlocking mechanisms such as retention holes and pins are also necessary[25,27]. To enhance bonding, a 3D-printed design can include a hollow structure within the zirconia teeth, allowing stronger mechanical interlocking with the denture base resin. This approach may reduce wall thickness, zirconia usage, and fabrication time. However, thinner walls may compromise the fracture resistance, necessitating the verification of the effects of wall thickness and resin presence on the fracture load.

This study aimed to determine the appropriate wall thickness of artificial zirconia teeth by verifying whether the wall thickness of hollow artificial zirconia teeth and the presence of resin inside the hollow structure affect fracture resistance. The two null hypotheses were that the fracture load of hollow-structured artificial zirconia teeth fabricated using a 3D printer was unaffected by either 1) wall thickness or 2) the presence of resin inside the hollow structure.

2. Materials and Methods

2.1. Production of samples

The production procedure diagram is shown in **Figure 1**.

2.1.1. Design data

The shape of the mandibular right first molar of a common size was used as a prototype artificial tooth. In a separate investigation[49], the accuracy of tooth fabrication was of interest; therefore, pairs of planar areas perpendicular to either the x- (mesiodistal), y- (lingobuccal), or z- (vertical) directions were created along the tooth surface. The specific dimensions of the artificial teeth were 10.9 mm, 9.8 mm, 7.0 mm, and 4.5 mm in the buccolingual, mesiodistal, verticobuccal and verticolingual directions, respectively. Based on the final outer tooth geometry with a circular hole of 3.0 mm in diameter in the center of the basal surface, walls with different thicknesses “b” (which was a variable used for “wall thickness” in this study) (0.30 mm, 0.50 mm, 0.75 mm, and 1.00 mm) were designed (Geomagic Design X 2022) on the inner side resulting in four different artificial tooth geometries with identical outer geometry and differing wall thicknesses (**Fig. 2**).

2.1.2. Fabrication of artificial zirconia teeth

Using the design data of the four hollow artificial teeth, identical support structures were placed on the mesial side (Geomagic Design X 2022; 3D Systems, Rock Hill, SC, USA). Since a total sample size of 73 was required to detect statistical differences with a power of 0.8 or greater (G*Power 3.1.9.7, Heinrich-Heine-Universität, Düsseldorf, Germany), 20 specimens for each condition were fabricated using a 3D printer (CeraFab 7500 Dental, Lithoz GmbH, Vienna, Austria) from tetragonial zirconia polycrystals containing 3 mol% yttria (LithaCon 3Y 210, Lithoz GmbH, Vienna, Austria) (**Table 2**). The specimens were cleaned, thermally pre-conditioned, debinded, and sintered for five

Table 2. Settings for the 3D printer and details of the zirconia material used in this study

3D printer settings	Processing method		Stereolithography
	Data format		.stl
	Light source		LED
	Light power		70 mW/cm^2
	Light direction		Bottom-up
	Lateral resolution		40 µm
	Layer thickness		25 µm
	Building envelope		76 x 43 x 170 mm^3
Details of the zirconia material	Slurry	Powder content [vol%]	48
	Sintered ceramic	Theoretical density [g/cm^3]	6.088
		Relative density [%]	99.4
		Relative permittivity (measured at 3 GHz)	27.6
		Dielectric loss tanδ (meausred at 3 GHz)	2.5×10^3
		Four-point bending strength [MPa]	940

Fig. 3. Image of the fabricated tooth

Table 3. Settings of the zirconia sintering program

Temperature [°C]		Time [h:min]
Start	End	
25	90	4:00
90	90	2:10
90	120	7:00
120	120	5:00
120	160	6:30
160	160	10:30
160	220	14:00
220	220	7:00
220	325	24:00
325	325	7:00
325	430	8:45
430	430	6:00
430	500	1:00
500	600	1:00
600	1250	6:30
1250	1450	1:00
1450	1450	2:00
1450	25	6:00
total time		119:25

days (**Fig. 3**). Although no separate preconditioning was performed in this study, a long and safe firing protocol was employed because of the complex geometry (**Table 3**). After sintering, the specimens were sandblasted with 50-µm alumina powder at 2.0 bar. The specimens were then ultrasonically cleaned with distilled water and dried.

2.2. Fracture load testing

To perform the fracture load tests, an acrylic resin block was fabricated to fix the artificial zirconia tooth, such that the z-axis of the tooth was oriented vertically in the test setup (**Fig. 4**). The upper surface of the block resembled the geometry of the basal side with an imprint of an artificial tooth enlarged by a gap of 0.2 mm. Thus, the range of placement of the artificial zirconia tooth in the denture base resin was predefined and standardized. Eighty resin blocks were fabricated using a 3D printer (MAX, Asiga, Sydney, Australia) (FREEPRINT denture; DETAX GmbH, Ettlingen, Germany) and artificial teeth and blocks joined with denture base resin (PalaXpress; Kulzer GmbH, Hanau, Germany). Half of the specimens in each test group had holes on the basal side sealed with resin in advance, creating subgroups of teeth that remained hollow (hollow teeth) or filled with resin (filled teeth) (n = 10).

The fabricated specimens were fixed within a universal testing device (Z005; Zwick/Roell, Ulm, Germany) to verify the fracture resistance. A steel sphere 6 mm in diameter was placed in the central fossa, creating three contact points with the occlusal surface. The sphere size was selected as an antagonist based on the requirement for three contact points on the occlusal surface[50]. Several spheres (6 mm, 8 mm, and 10 mm) were tested using an articulating paper,

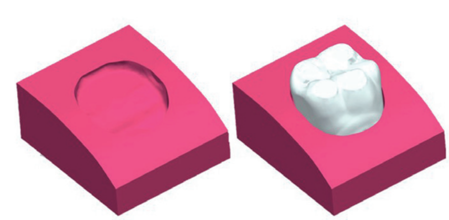

Fig. 4. Design images of the resin block for fracture load resistance test. Left: image of the resin block, right: image of the tooth placed on the resin block.

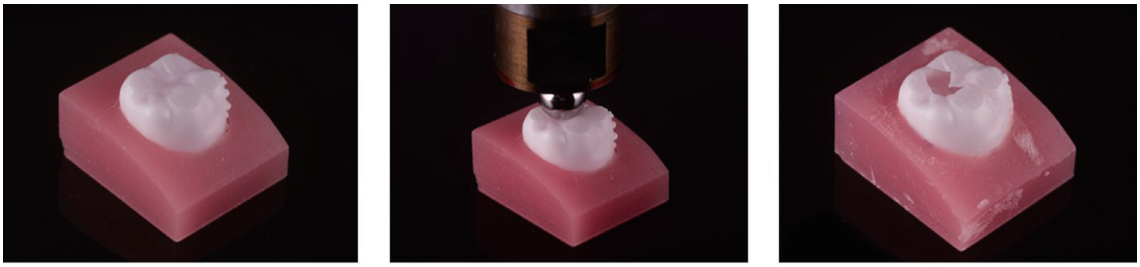

Fig. 5. Images of the fracture load resistance test. Left: before the test; center: fracture load testing; right: after the test.

Table 4. Overview of the results for the fracture tests for test groups differing in zirconia wall thickness and resin filling

Wall thickness [mm]	Resin filling	Fracture resistance F_u [N]						
		Mean	SD	Min	Q_1	Median	Q_3	Max
0.30	without	89	23	63	76	82	114	125
	with	172	57	96	133	171	188	303
0.50	without	229	54	145	193	217	275	322
	with	238	49	173	186	234	281	300
0.75	without	529	78	400	494	534	589	670
	with	487	150	311	390	462	522	822
1.00	without	764	140	556	685	748	828	1014
	with	895	314	592	701	799	897	1575

Q1=Lower quartile, Q3=Upper quartile.

and the most realistic positioning of the contact points was achieved with a 6 mm sphere in this study.

The sphere was loaded vertically using an indenter free of transverse forces at a crosshead speed of 1.0 mm/min until it fractured. The maximum measured test force (F_u) was defined as the fracture resistance, and we calculated the mean maximum measured test force ($F_{u\ mean}$) (**Fig. 5**).

2.3. Fracture mode

After fracture resistance tests, each artificial tooth was examined using a digital microscope (Smartzoom5; Carl Zeiss AG, Oberkochen, Germany) to observe the occlusal and fractured surfaces of the specimens. Representative specimens were further observed using a scanning electron microscope (SEM) (JSM-6510; JEOL, Tokyo, Japan) to identify the fracture modes and possible material imperfections contributing to premature fracture.

2.4. Statistical analysis

Statistical software (IBM SPSS Statistics, v29; IBM Corp., Armonk, NY, USA) was used for the statistical analyses. Because the fracture resistance data were heteroscedastic with regard to wall thickness, ranks were formed based on fracture resistance. The ranked data were normally distributed (Shapiro–Wilk test, QQ plots) and homoscedastic (Levene test). The effects of wall thickness and resin filling were analyzed using two-way ANOVA and Tukey's post-hoc tests based on ranked data. Additional pairwise *t*-tests were conducted between the groups with and without resin filling. The level of significance was set at 5%.

3. Results

3.1. Fracture resistance

The results of fracture resistance tests are summarized in **Table 4**.

Two-way ANOVA revealed significant differences between the test groups concerning wall thickness ($P < .001$) but not with regard to resin filling ($P = .150$). Tukey tests revealed three homogeneous subgroups: artificial teeth with wall thicknesses 1) b = 0.30 mm and b = 0.50 ($F_{u,mean} = 131$ N and $F_{u,mean} = 233$ N, respectively), 2) b = 0.75 mm ($F_{u,mean} = 508$ N), and 3) b = 1.00 mm ($F_{u,mean} = 829$ N). T-tests between the corresponding groups with and without resin filling only identified significant differences for artificial teeth with the thinnest walls, that is b = 0.30 mm.

For bending-dominated problems, fracture load should increase broadly proportional to the square of wall thickness, i.e., $F_u \sim b^2$. **Figure 6** shows the measured fracture forces (F_u) versus the respective squares of the wall thickness. A regression line without an intercept was added to the artificial teeth without filling, which fit the data well ($R^2 = .97$). Regression provided a correlation of $F_u = 812$ N/mm$^2 \cdot b^2$. Filled teeth differed significantly from this behavior only for b = 0.30 mm, with fracture forces almost doubling due to resin filling ($r_F = F_{u,filled}/F_{u,hollow} = 1.93$, $P < .001$).

3.2. Fracture mode

Microscopy revealed that most occlusal surfaces of the hollow teeth were completely fractured, whereas all the fracture surfaces of the filled teeth were incompletely fractured. The fracture surfaces of the specimens are smooth and uniform (**Fig. 7**).

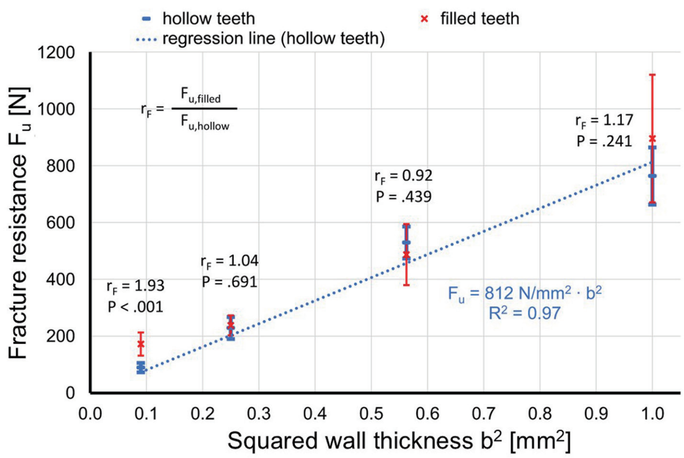

Fig. 6. Graph image of fracture resistance and regression line

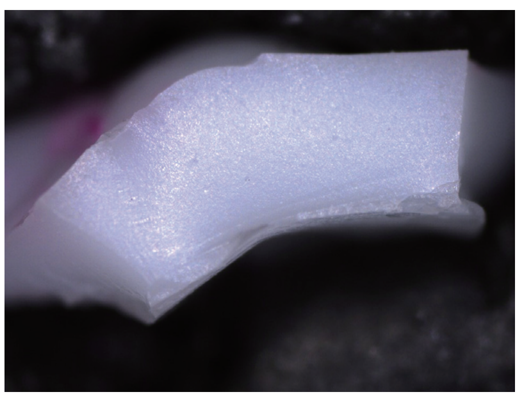

Fig. 7. Representative microscopy image of the fracture surface

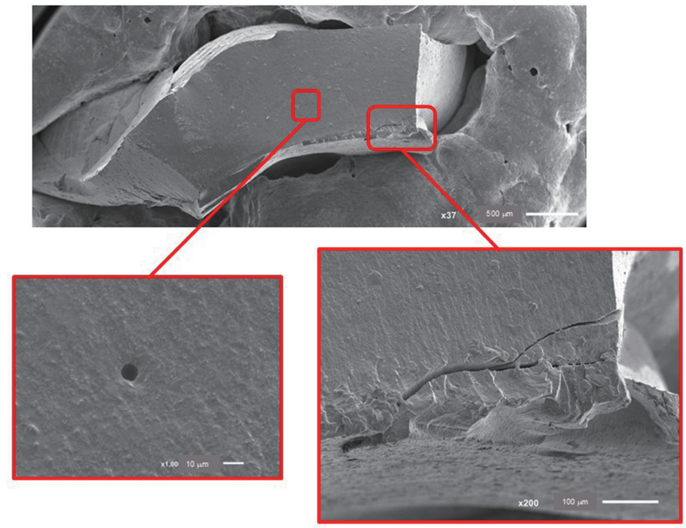

Fig. 8. Representative SEM images of the void and fracture line. Top: ×37 image, left: ×1000 image, right: ×200 image.

Subsequently, the fracture surfaces of the selected specimens were examined using SEM to confirm the fracture lines and voids, and few voids were observed. The diameters of voids were all within 10 µm. Fracture lines were observed on the surface layer of the internal hollow structure side but not on the occlusal surface of the artificial teeth (**Fig. 8**).

4. Discussion

This study investigated the effects of wall thickness and presence of an underlying resin on the fracture resistance of artificial zirconia teeth with a hollow structure. To the best of our knowledge, this is the first study to assess the influence of wall thickness on the fracture resistance of artificial hollow zirconia teeth.

In this study, the fracture resistance of artificial zirconia teeth increased significantly with the wall thickness, leading to rejecting null hypothesis 1. Null hypothesis 2, which proposed that resin filling would not affect fracture resistance, was rejected only for teeth with very thin walls (b = 0.30 mm).

When evaluating the fracture resistance required for artificial teeth, multiple factors must be considered[51–54]. Previous research has examined the fracture resistance of first premolar resin teeth fabricated using 3D printing. It has been reported that premade artificial resin teeth have fracture resistances ranging from approximately 80 N to 250 N, while 3D-printed artificial resin teeth exhibit a fracture resistance of approximately 160 N[51]. A different tooth shape was used for the artificial teeth in the present study (molar instead of premolar). However, the thresholds given in the text above were defined for all teeth in the posterior region. Furthermore, previous studies on occlusal forces have reported that age, sex, denture use, and denture type influence occlusal force[52–54]. Considering these findings, a fracture load of approximately 300 N is sufficient for an artificial tooth.

Applying results of previous studies to the present study, it was observed that teeth with b = 0.30 mm were inadequate for clinical use, with mean fracture forces below 173 N and minimum fracture forces below 97 N. Mean fracture resistance of artificial zirconia teeth with b = 0.50 mm was approximately 250 N, but the lowest recorded fracture resistances were below 173 N. The first groups offering promising fracture resistance showed a wall thickness of b = 0.75 mm, with all tested zirconia teeth exceeding a fracture force of 310 N and with a mean fracture resistance close to 500 N. Artificial teeth of the last two test groups (b = 1.0 mm) fractured above 555 N. Therefore, based on the present data, clinical use of artificial 3D-printed zirconia teeth can be recommended only for wall thicknesses of b = 0.75 mm or higher. If high bite forces are expected, a thickness of at least b = 1.00 mm should be used.

Regarding zirconia crowns, one study reported that as the thickness of the margin decreased, fracture resistance decreased significantly[35]. Similarly, in this study, the fracture resistance decreased significantly as the wall thickness decreased. As expected for a bending-dominated problem, the square of the wall thickness was proportional to the fracture resistance. As shown in **Figure 6**, thin-walled teeth (b = 0.30 mm) with resin filling were the only test group that did not fit well with the overall behavior. This group showed the highest relative increase in fracture resistance due to resin filling because the deflection of the zirconia wall at fracture for bending-dominated problems was proportional to b^{-1}. Thus, the supporting force provided by the filling increased with decreasing wall thickness. With a wall thickness of b = 0.30 mm, the mean fracture forces could be increased by resin filling from 89 N to 172 N. With higher wall thicknesses, this absolute difference decreases, and the relative effect decreases further as the total fracture force increases tremendously with increasing wall thickness. If the filling significantly affects the fracture force of artificial teeth, the material used for filling should have a higher Young's modulus. Therefore, the use of highly filled composite resins is of great interest.

However, the filled teeth showed results far from the regression line for the 0.30 mm condition. Thus, filled teeth showed higher fracture resistance than hollow teeth only under the 0.30 mm condition, providing a statistically significant difference. However, no significant difference in fracture resistance was observed between the hollow and filled teeth under other conditions. This might be because the fracture resistance of zirconia teeth with a wall thickness of 0.30 mm was lower than that of the denture base resin and was enhanced by the filled resin. Conversely, walls thicker than 0.50 mm showed fracture resistance higher than that of the filled resin, indicating that the denture base resin did not contribute to the fracture resistance of the teeth. Because the maximum deflection of a material is inversely proportional to the material thickness, the thinner the material, the greater the deflection. Thus, the deflection with a thickness of 0.30 mm was larger than that under other conditions, suggesting that the resin inside the tooth supported the deflection. Thus, the presence of resin inside the tooth affected fracture resistance below a wall thickness of 0.30 mm but not above 0.50 mm.

However, based on the microscopy and SEM observation results, it is believed that filling the interior of the artificial tooth with resin is beneficial, regardless of the wall thickness, in preventing the risk of a complete fracture in the mouth. Unlike hollow teeth, optical microscopy showed no filled teeth underwent a complete fracture on the occlusal surface. In addition, fracture lines in the artificial teeth were observed on the hollow-structure side based on the results of the SEM observation. This suggests that when the load was applied vertically from the occlusal surface, the stress was concentrated on the internal hollow structure, resulting in fracture. This is presumably because the support from the filled resin prevented the complete fracture of the zirconia artificial tooth.

As a result, a zirconia wall thickness ≥0.75 mm seems to offer sufficient fracture resistance for an artificial tooth, regardless of the presence of resin. Nonetheless, filling the interior of artificial zirconia teeth with resin may be useful to prevent the risk of complete fracture.

Detailed observation of the fracture surface in artificial zirconia teeth using SEM revealed that the number of voids was small. Thus, the internal properties of the printed zirconia were relatively uniform. Thus, the fabrication process for artificial zirconia teeth in this study showed no major problems, although improvements to reduce the sintering time are still needed.

It should be noted that milling a hollow-structured zirconia artificial tooth, as designed and fabricated using 3D printing in this study, is not technically feasible. Consequently, a control group using conventional techniques such as milling was not included. Nonetheless, future studies should conduct comparative analyses between this 3D-printing method and other established fabrication techniques. Such comparisons are critical for further validating the clinical relevance and assessing the potential advantages of 3D-printed artificial zirconia teeth.

The right mandibular first molar was used as an artificial tooth. The reasons were as follows: the zirconia material used in this study was a non-translucent type and inappropriate for use in anterior teeth esthetically; the fracture resistance of the first molars is important because these teeth experience the greatest occlusal load; and if the occlusal vertical dimension is stable in the molar region, a more esthetic artificial tooth can be used for anterior teeth. Therefore, the results may differ for highly translucent artificial zirconia teeth used as anterior teeth. Further investigation of these issues is required.

In addition, this study used small holes on the basal surface of the teeth that were similar in size to those of ready-made porcelain artificial teeth. The fracture resistance of an artificial tooth may be affected by changing the size and shape of these small holes, which warrants further research.

In this study, it was crucial to understand the mechanisms by which resin filling enhances strength. Although this study showed that resin filling improves fracture resistance, especially in thinner walls, further investigation is required to understand how the properties and placement of the filling material affect this resistance. For example, systematically evaluating the impact of different types of resin materials, such as composite resins, and various filling techniques on the strength could lead to the development of more durable artificial teeth. In addition, long-term studies are required to assess the effects of resin filling on the long-term durability and wear resistance of zirconia.

Finally, the development of customized artificial teeth that meet the individual needs of patients is essential. Designing artificial teeth based on the occlusal force and pattern of each patient can reduce the risk of damage and improve comfort. This could include personalized designs based on the intraoral scan data for each patient and automation of the optimal design using artificial intelligence.

5. Conclusions

In conclusion, these results suggest that the wall thickness of hollow-structured zirconia artificial teeth affects the fracture resistance. Still, the presence of resin inside does not affect the fracture resistance if the wall thickness is ≥0.50 mm. The results also suggest that artificial zirconia teeth offer sufficient fracture resistance for clinical use when the wall thickness is ≥0.75 mm, regardless of the presence of filling.

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Conflict of interest statement

There are no conflicts of interest to declare regarding this study.

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