ORIGINAL RESEARCH

Comparison of Fracture Resistance Force (Load-to-fractured Test) and Failure Type of 3D-printed Stainless Steel Crowns and Preformed Stainless Steel Crowns in Primary Molars: An *In Vitro* Study

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Abstract

Aims and background: This study aims to compare the fracture resistance force (FRF) and failure types of three-dimensional (3D)-printed stainless steel crowns (SSCs) and preformed SSCs in primary molars.

Materials and methods: Forty-eight over-retained and extracted mandibular second deciduous molars were divided into two groups: one receiving 3D-printed crowns and the other preformed crowns. Fracture resistance testing was performed using a universal mechanical testing machine, and failure types were analyzed post-testing.

Results: Fracture resistance testing revealed a significant difference between 3D-printed and preformed SSCs ($p < 0.05$), with 3D-printed crowns exhibiting a mean FRF of 3953.82 N compared to 742.94 N for preformed crowns. Additionally, Mann–Whitney *U* tests and Chi-squared tests were utilized to examine variations within and across the groups. Analysis of shear bond strength showed that 3D-printed crowns demonstrated superior adhesive performance compared to preformed crowns, with mean shear bond strength values of 3953.82 N and 742.94 N, respectively. Both groups A and B showed unrepairable failure modes.

Conclusion: The study concludes that 3D-printed SSCs offer distinct advantages over preformed options, including tailored fit, enhanced mechanical properties, and improved longevity. These findings underscore the potential of 3D printing technology to revolutionize pediatric dental restoration practices.

Clinical significance: Integrating 3D printing into pediatric dental practice holds promise for optimizing treatment outcomes and improving long-term oral health in children. The superior fracture resistance and adhesive performance of 3D-printed crowns suggest their potential to enhance restoration viability and reduce the need for subsequent interventions.

Keywords: Computer-aided design/computer-assisted milled crowns, Direct metal laser sintering printing technology, Fracture resistance force, Preformed crowns, Primary molars, Stainless steel crowns, Three-dimensional printed crowns.

International Journal of Clinical Pediatric Dentistry (2024): 10.5005/jp-journals-10005-2977

Introduction

Dental caries is a significant global health concern, especially among young children. The decayed primary teeth need to be restored and preserved as they play a crucial role in chewing, speaking, and esthetics, and most importantly act as a natural space maintainer for the succedaneum teeth in the dental arch.[1] Stainless steel crowns (SSCs) have traditionally been regarded as the benchmark for restoring primary teeth due to their durability and cost-effectiveness. However, they are not without limitations, including their preformed shapes and sizes, which might not perfectly match every child's tooth anatomy.[2] This can lead to less-than-ideal fits in some cases. Fitting a permanent molar stainless steel crown requires significantly more chairside time which can be a potential problem while treating very young or uncooperative children.

The recent advancements in digital dentistry such as three-dimensional (3D) printing and computer-aided design/computer-aided manufacturing (CAD/CAM) technology have revolutionized crown fabrication offering a custom fit and highly precise restoration.[3]

In 3D printing, objects are created through an automated process of layering materials to form a volumetric structure. Direct metal laser sintering (DMLS), an advanced additive manufacturing technology, uses this approach to fabricate high-precision metal parts. The process begins with Exocad software, which converts 3D CAD data into two-dimensional (2D) cross-sections. These cross-sections serve as blueprints for the DMLS machine, guiding the laser on where to sinter the material. A fine layer of metal powder is uniformly applied over the build platform, and a laser selectively

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How to cite this article: Giridharan DL, Gopal S. Comparison of Fracture Resistance Force (Load-to-fractured Test) and Failure Type of 3D-printed Stainless Steel Crowns and Preformed Stainless Steel Crowns in Primary Molars: An *In Vitro* Study. Int J Clin Pediatr Dent 2024;17(10):1129–1134.

Source of support: Nil

Conflict of interest: None

fuses the material according to the 2D design. After each layer is sintered, the platform descends slightly to accommodate the next layer. Once the part is complete, it undergoes age-hardening heat treatment to enhance its strength, followed by finishing with a polishing tool or wheel bur to achieve the desired surface smoothness.[4]

Its advantages include its ease and quick fabrication with lesser material wastage, superior diagnostic, and full mechanical and functional efficacy. When comparing 3D-printed restorations to those fabricated through conventional methods, 3D printing stands out due to its superior precision, accuracy, detailed recording capability, high-quality, and finely finished restorations. Among all available dental processing techniques, 3D printing has emerged as the preferred method. However, to the best of our knowledge, no studies have yet been conducted to evaluate the fracture resistance force (FRF) and fracture patterns of these materials when cemented onto primary teeth. Therefore, the aim of this *in vitro* study is to compare the FRF (load-to-fractured test) and failure type of two types of crowns in primary molars: 3D-printed SSCs using DMLS technology and preformed SSCs.

Materials and Methods

The aim of this study was to compare the FRF and failure type of 3D-printed SSCs, produced through DMLS technology, with preformed SSCs in primary molars. The sample size was 48 and they were sourced from primary mandibular second molars extracted due to over-retention, obtained from the department of pediatric and preventive dentistry and private clinics in the area. Inclusion criteria comprise sound crowns of primary mandibular second molars, while exclusion criteria include teeth with cavitated carious lesions, internal resorption, restorations, fractures, cracks, or developmental defects.

The study utilized 48 over-retained and extracted mandibular second deciduous molars, dividing them into two groups of 24 each. One group received 3D-printed SSCs manufactured *via* DMLS technology, while the other group received prefabricated SSCs.

After collection, the teeth were stored in a thymol-saturated solution for a period of 7 days. Then, the teeth were thoroughly rinsed and cleaned using distilled water to remove any residual thymol solution and debris. Subsequently, the selected teeth were embedded in 1 × 1 inch acrylic resin blocks (Fig. 1).

The teeth were then divided into two groups: group A and group B. Group A received preformed SSCs, while group B received 3D-printed SSCs fabricated using DMLS technology.

Preformed SSCs for group A were selected to fit the size of the mandibular second primary molar. Subsequently, all samples underwent crown cutting preparation, involving slicing of the mesial and distal surfaces and breaking of contact using a tapering fissure bur. The bur was held at an angle to the long axis of the tooth and the slicing is extended to the buccal and lingual walls, giving it a 2–5° taper. The buccal and lingual preparation is done at the occlusal one-third using a tapered fissure bur at a 30–45° angle to occlusal surfaces. The preformed crowns were subsequently tried on to verify their fit, and any prominent undercuts in the prepared teeth were eliminated using a finishing bur (Fig. 2).

In contrast, teeth in group B underwent a different process. Crown designs for these teeth were generated using Exocad GMBH software. The CAD was then transferred to a DMLS machine, and the 3D image was mathematically sliced into 2D cross sections, each of these sections acted as a blueprint that utilized laser technology to selectively sinter metal powder, layer by layer, according to the digital design (Fig. 3). This process resulted in the fabrication of 3D-printed SSCs with precise dimensions and customized features (Fig. 4).

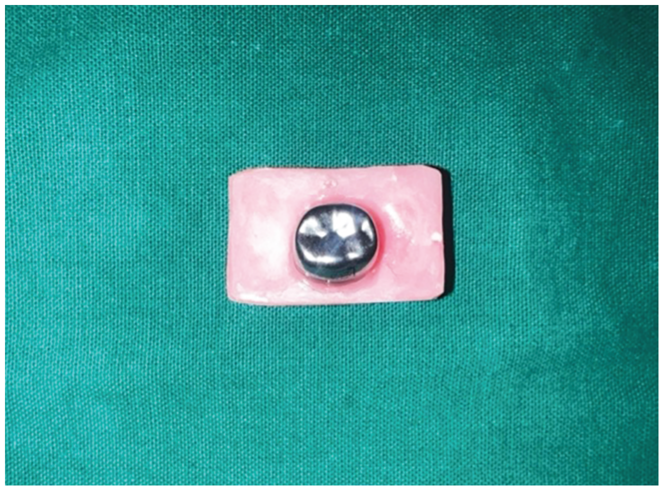

Fig. 2: Preformed SSCs

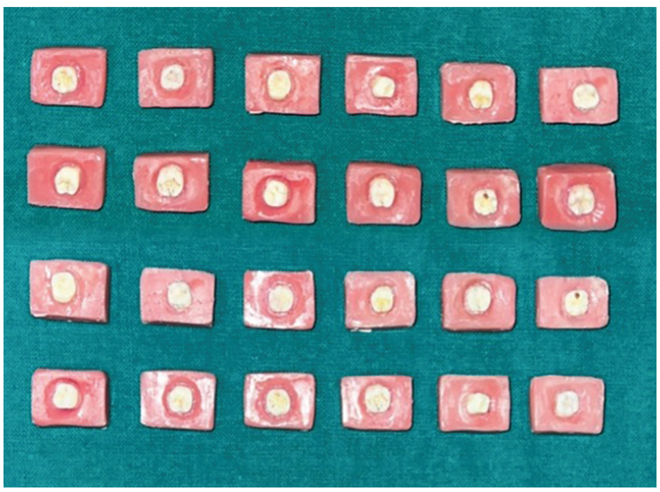

Fig. 1: Extracted teeth mounted on acrylic blocks

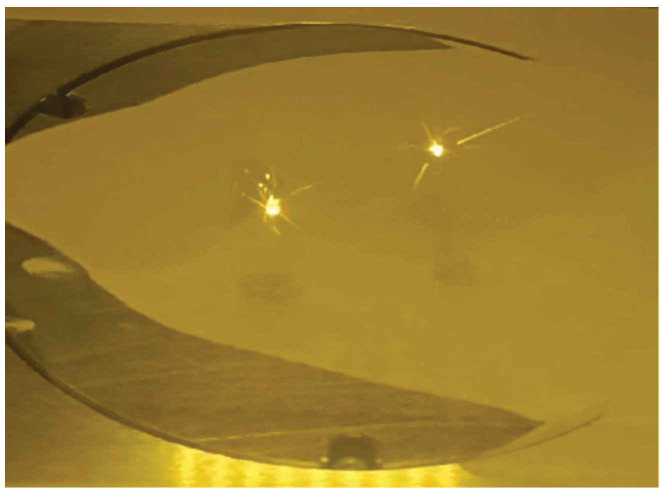

Fig. 3: 3D printing of the crowns using DMLS technology

Once the crowns were fabricated, they were tried on the prepared teeth to ensure a passive fit (Fig. 5). Any remaining undercuts in the prepared teeth were removed as necessary with a composite finishing bur. After confirming the proper fit, the crowns from both groups (A and B) were cemented onto their respective teeth.

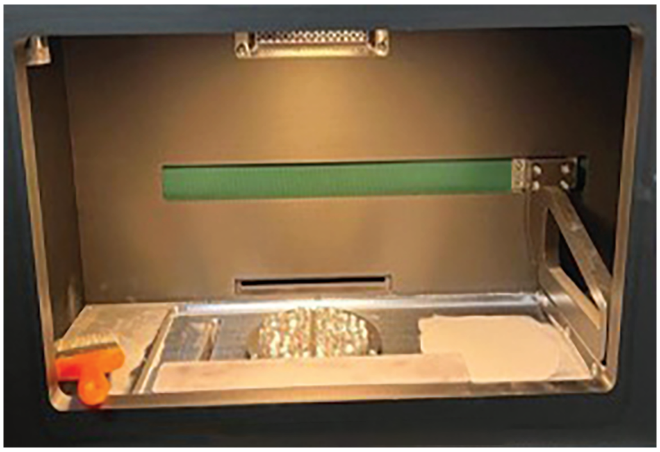

Fig. 4: Sintered crowns in the 3D printing machine

Subsequently, fracture resistance testing was performed on each crowned tooth in both groups using a universal mechanical testing machine. This machine applied uniaxial force to the crowns through a stainless steel ball fixture, simulating occlusal loading conditions (Fig. 6). The force was gradually increased until the crown fractured. Following the load-to-fracture tests, the samples were carefully analyzed to determine the type of failure exhibited. Possible failure types included repairable or unrepairable fractures.

Results

Initial normality testing using the Shapiro–Wilk test indicated that the data did not conform to a normal distribution ($p < 0.05$), prompting the utilization of nonparametric tests for subsequent analyses (Table 1). FRF of preformed crowns exhibited a mean FRF of 742.94 ± 145.16, while 3D crowns demonstrated a substantially higher mean FRF of 3953.82 ± 72.33 (Table 2 and Fig. 7).

The mean shear bond strength for preformed crowns is 742.94079 with a standard deviation of 145.1582, while the mean shear bond strength for 3D crowns is 3953.817 with a standard deviation of 72.33164. The 3D crowns demonstrated lower variability in fracture resistance, as indicated by their smaller

Fig. 5: 3D-printed metallic crowns using DMLS technology

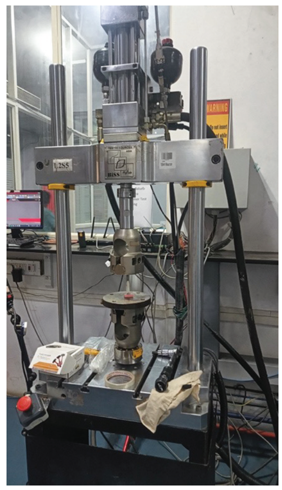

Fig. 6: Universal testing machine applying uniaxial force

Table 1: Normality testing

Tests of normality						
	Kolmogorov–Smirnov[a]			*Shapiro–Wilk*		
	Statistic	*df*	*Sig.*	*Statistic*	*df*	*Sig.*
3D	0.378	24	0.000	0.556	24	0.000
Preformed	0.203	24	0.012	0.859	24	0.003

[a]Lilliefors significance correction; There is a statistical difference reported in normality testing; hence, the data does not follow normal distribution and nonparametric test was applied for the analysis

Table 2: Descriptive details of the groups—fracture resistance

	N	*Minimum*	*Maximum*	*Mean*	*Std. error*	*Std. deviation*	*Variance*
Preformed	24	487.076	901.481	742.94079	29.6303	145.1582	21070.91
3D	24	3797.33	3993.16	3953.817	14.7646	72.33164	5231.867

The mean fracture resistance for preformed crowns is 742.94079 with a standard deviation of 145.1582; The mean fracture resistance for 3D crowns is 3953.817 with a standard deviation of 72.33164; The Mann–Whitney U test indicates a significant difference in fracture resistance between the two groups ($p < 0.05$)

standard deviation (72.3316) and variance (5231.86) compared to the preformed crowns (standard deviation: 145.158230, variance: 21070.912) (Table 3).

Both Mann–Whitney *U* tests and Chi-squared tests were utilized to examine variations both within and across the groups. The outcomes revealed a noteworthy distinction in fracture resistance between 3D and preformed crowns ($p < 0.05$), indicating that 3D crowns exhibited notably enhanced resistance to fracture compared to their preformed counterparts (Tables 4 and 5 and Fig. 8).

Conversely, no statistically significant differences were observed in failure modes between the groups. This comprehensive analysis underscores the efficacy of nonparametric tests in evaluating dental crown properties and emphasizes the potential benefits of 3D crown fabrication techniques in enhancing fracture resistance (Table 6 and Fig. 9).

Discussion

Stainless steel crowns have long been a cornerstone of pediatric dentistry, offering a durable and reliable solution for restoring decayed or damaged primary teeth (Bakland).[5] They provide full coverage restoration and are particularly beneficial in cases where extensive decay necessitates robust support beyond traditional fillings. Their inherent strength and durability allow them to withstand the rigorous biting forces and chewing habits typical of children, while also serving as a protective barrier against further decay or damage, especially crucial in instances where children may struggle with maintaining optimal oral hygiene. The challenges posed by managing pulpotomized primary molars with extensive cavity preparations underscore the necessity for effective restorative solutions.

Preformed SSCs have emerged as a preferred choice in pediatric dentistry for such cases, offering several advantages.

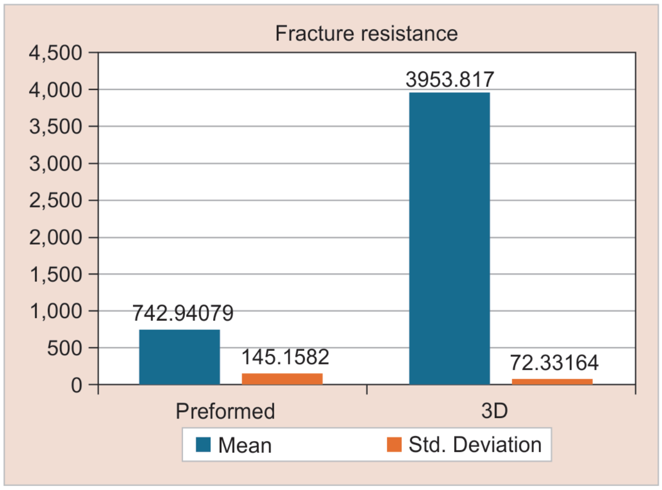

Fig. 7: The mean FRF of preformed crowns and 3D-printed crowns

Table 4: Comparison of fracture resistance using Mann–Whitney *U* test

Ranks				
	Groups	*N*	*Mean rank*	*Sum of ranks*
Fracture resistance	3D crowns	24	36.50	876.00
	Preformed crowns	24	12.50	300.00
	Total	48		

The Mann–Whitney *U* test shows a significant difference in fracture resistance between 3D and preformed crowns ($p < 0.05$); The mean rank for fracture resistance is higher for 3D crowns compared to preformed crowns

Table 5: Mann–Whitney *U* analysis

Test statistics[a]	
	3D
Mann–Whitney *U*	0.000
Wilcoxon W	300.000
Z	–5.973
Asymp. Sig. (two-tailed)	0.0001*

[a]Grouping variable: groups; *$p < 0.05$ is statistically significant (Shapiro–Wilkinson test, $p > 0.05$); The Mann–Whitney *U* test confirms the significant difference in fracture resistance between the two groups ($p < 0.05$); Shapiro–Wilkinson test for normality reported significant difference ($p < 0.05$), Hence, nonparametric tests are used for the analysis. Regarding fracture resistance, group analysis by Mann–Whitney *U* test reported a significant difference ($p < 0.05$) (3D > preformed)

Table 3: Descriptive details of the groups (shear bond strength)

		Preformed	*3D*
Mean		742.94079	3953.817
95% confidence interval for mean	Lower bound	681.64585	3923.27486
	Upper bound	804.23574	3984.36081
5% trimmed mean		748.34771	3960.325
Median		751.95400	3988.679
Variance		21070.912	5231.86
Std deviation		145.158230	72.3316
Minimum		487.076	3797.33
Maximum		901.481	3993.16
Range		414.405	195.830
Interquartile range		193.116	31.290
Skewness		–0.648	–1.817
Kurtosis		–0.718	1.577

The mean shear bond strength for preformed crowns is 742.94079 with a standard deviation of 145.1582; The mean shear bond strength for 3D crowns is 3953.817 with a standard deviation of 72.33164; The data includes confidence intervals, trimmed mean, median, variance, range, interquartile range, skewness, and kurtosis for both groups

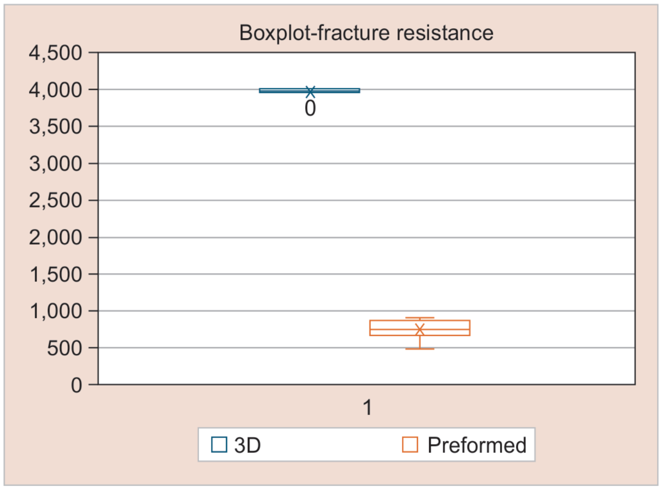

Fig. 8: The comparison of FRF of preformed crowns and 3D-printed crowns

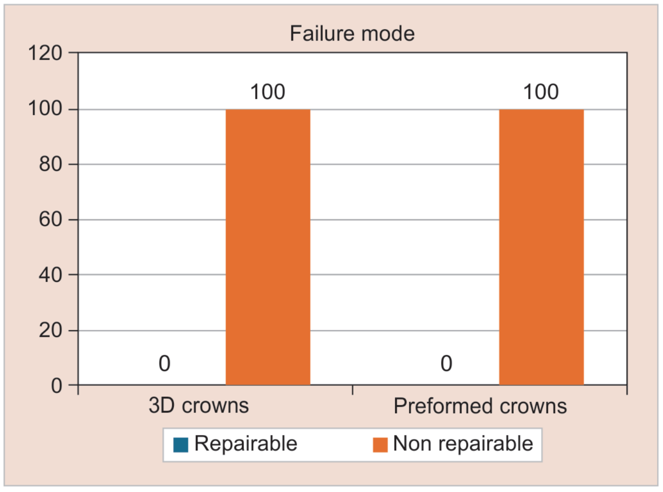

Fig. 9: The comparison failure mode of preformed crowns and 3D-printed crowns

Table 6: Failure mode comparison

	Repairable	*Nonrepairable*	*Chi-squared test*
3D crowns	0	24 (100%)	0.99
Preformed crowns	0	24 (100%)	

*$p < 0.05$ is statistically significant; Chi-squared tests were conducted to compare failure modes between 3D and preformed crowns; The results show no statistically significant difference in failure modes between the two groups ($p > 0.05$)

These crowns exhibit exceptional durability, ensuring long-term restoration viability, and provide superior protection to the remaining tooth structure, thus minimizing the risk of recurrent decay or damage. Moreover, their biocompatibility and cost-effectiveness further enhance their appeal as a pragmatic choice for pediatric patients.

However, while preformed crowns offer convenience and affordability, they are not without limitations. Their standardized sizes and shapes may lead to imperfect fits and esthetic concerns, potentially necessitating additional adjustments or replacements. Moreover, the lack of customization restricts their ability to address specific patient needs or preferences, potentially compromising treatment outcomes. These drawbacks highlight the importance of considering alternative approaches, particularly in the context of emerging technologies.

Recently, there has been an increased interest in the use of full-coverage crowns for the pediatric population. A thorough investigation of the literature reveals that several factors play a pivotal role in the fracture resistance of these crowns. One critical element is the material from which the crown is fabricated. The integration of 3D printing technology represents a significant advancement in modern dentistry, offering unparalleled customization and precision in dental prosthetic fabrication, including SSCs (Kattadiyil et al.).[6] Unlike preformed crowns, 3D-printed counterparts can be tailored precisely to individual tooth dimensions and contours, ensuring optimal fit and esthetics. This level of customization, coupled with the flexibility to create complex shapes and intricate details, positions 3D-printed crowns as a promising alternative with superior mechanical properties, and durability (Mangano et al.).[7] This is supported by the study done by Oƒüuz et al.,[8] in their *in vitro* study compared the fracture resistance and survival of various esthetic crowns for primary molars after artificial aging through chewing simulation. CAD/CAM zirconia (CZ) crowns exhibited the highest fracture resistance, surpassing other groups, with no microcrack formation observed after aging. The findings suggest that CAD/CAM CZ crowns may offer prolonged service life and superior fracture resistance compared to other fabrication methods, highlighting the importance of fabrication techniques in determining the mechanical properties and durability of dental crowns.

Different materials, such as stainless steel or CZ, have varying levels of strength and durability, affecting the crown's ability to withstand forces applied during mastication in children (Ahmad et al.).[9] Additionally, the design of the crown, including thickness and contour, plays a significant role in its fracture resistance. Crowns with thicker walls and well-defined anatomical features are more likely to distribute forces evenly and resist fracture.

For the primary molars, the mean maximum bite force measures 76 newton (unit of force) (N) for children aged 6–8 years and increases to 106 N for those aged 10–12 years. The average force values required to fracture the crowns manufactured using 3D printing technology were 3954 N and 743 N for preformed SSCs. These values are above the average maximum occlusal load of 738 N of an adult, as determined by Braun et al.[10] Hence, the mean force required to fracture the 3D-printed crowns surpassed the reported mean maximum bite force values, demonstrating superior fracture resistance compared to the average bite force.

Al-halabi et al.,[11] in their study, compared the FRF and failure type of three esthetic crowns for primary molars. Results showed that the mean force required to fracture the crowns was highest for CAD/CAM (1719 N), followed by 3D printable resin (1494.05 N), and lowest for direct composite celluloid crowns (879.51 N). Interestingly, indirect crowns (CAD/CAM and 3D printable resin) exhibited "not repairable" fractures, these findings closely align with our study's outcomes where superior fracture resistance of 3D-printed crowns over conventional options, emphasizing the potential advantages of emerging fabrication methods in enhancing dental restoration outcomes showed superior fracture resistance over conventional options, emphasizing the potential advantages of emerging fabrication methods in enhancing dental restoration outcomes.

Similarly, our analysis of shear bond strength revealed substantial differences between the two groups, with 3D-printed crowns demonstrating superior adhesive performance. This finding aligns with recent studies demonstrating the favorable bonding characteristics of 3D-printed dental restorations, which can be attributed to the absence of voids or defects commonly encountered in conventionally fabricated crowns (Revilla-León et al.).[12] The higher shear bond strength observed in 3D-printed crowns underscores the potential of additive manufacturing to enhance the longevity and stability of dental restorations, ultimately improving clinical outcomes for patients (Alharbi et al.).[13]

Contrary to expectations, our analysis of failure modes using the Chi-squared test revealed no statistically significant difference ($p > 0.05$) in the distribution of failure modes (repairable vs nonrepairable) between the two crown types. While previous research has suggested that fabrication methods may influence the prevalence of specific failure mechanisms, our findings suggest that other factors, such as material composition or clinical variables, may exert a more substantial impact on the susceptibility to failure (Li et al.).[14] This underscores the multifactorial nature of dental restoration failure and highlights the importance of considering various clinical variables in treatment planning and prognostication.

Within the limitations of this study, it was concluded that both, 3D-printed and preformed SSCs tested surpassed the average maximum bite force of children in primary dentition. The study's limitations come from: (1) the use of naturally extracted teeth, (2) the cement film thickness, and (3) differences in the dimensions of these molars. To address this issue and strive for uniformity, the Exocad GMBH software (Darmstadt, Germany) was utilized. Its purpose was to generate consistent thickness at the interface between the tooth and the inner surface of the crowns cemented onto the prepared teeth in group B and (4) there could be a potential underestimation of the force necessary to fracture the crowns *in vivo*. This suggests that the study might have observed higher values for the force required to fracture the crowns if a more accurate measurement had been obtained.

Conclusion

In conclusion, while preformed SSCs have long been a mainstay in pediatric dentistry, advancements in 3D printing technology offer compelling advantages in terms of customization, mechanical properties, and longevity. As the field continues to evolve, further research and clinical validation are warranted to optimize the integration of these innovative approaches and ensure superior outcomes for pediatric patients.

Clinical Significance

The study addresses the clinical significance of managing severe caries in primary molars, crucial for children's oral health. SSCs have long been utilized, yet limitations like standardized sizing and esthetic concerns persist. Leveraging digital advancements like enhanced mechanical properties and precise customization contributes to prolonged restoration viability, minimizing the need for replacements and subsequent interventions. Moreover, the favorable bonding characteristics of 3D-printed crowns suggest improved longevity and stability, crucial for long-term oral health outcomes in pediatric patients.

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