ORIGINAL ARTICLE

EFFECT OF CAD DESIGN ON THE MECHANICAL RESISTANCE OF 3D-PRINTED SPACE MAINTAINERS: AN IN VITRO STUDY

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Abstract: *Background*: Three-dimensional (3D) printing has emerged as a promising approach for the fabrication of customized space maintainers. However, limited information is available regarding the influence of CAD design on their mechanical performance. Aim: The aim of this study was to evaluate the effect of CAD design on the mechanical strength of 3D-printed space maintainers fabricated using a photopolymer dental resin. *Materials and Methods*: Three space maintainer designs were investigated: a standard digital model obtained from an online library (G1) and two customized CAD designs (G2 and G3). Statistical analysis included descriptive statistics, the Shapiro–Wilk test, Levene's test, and an independent-samples Student's t-test ($p < 0.05$). *Results*: All specimens in G1 fractured before mechanical testing and were excluded from statistical analysis. Mean fracture-load values were 52.32 ± 17.55 N for G2 and 94.40 ± 13.63 N for G3. Statistical analysis demonstrated a significant difference between the two CAD designs ($t(12) = -5.01$, $p = 0.0003$), with G3 showing superior mechanical resistance. *Conclusions*: CAD design significantly influenced the mechanical performance of the investigated space maintainers. The customized design with reinforced critical areas exhibited substantially greater fracture resistance, suggesting that geometric optimization may enhance the structural reliability of 3D-printed space maintainers.

Keywords: space maintainer; CAD design; 3D printing; LCD printing; fracture resistance; pediatric dentistry; additive manufacturing.

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1. Introduction

Premature loss of primary teeth is a frequently encountered condition in pediatric dentistry and may have a considerable impact on the proper development of the dental arches. Early extraction of primary molars can alter the dentoalveolar balance, promoting movement of neighboring teeth, decreasing arch length, reducing the space available for eruption of permanent successors, and increasing the risk of developing malocclusions that may later require orthodontic correction [1,2].

Maintaining arch space after the early loss of a primary tooth is a key objective of interceptive dental care. Space maintainers are appliances intended to preserve the available space until the eruption of the permanent replacement tooth. These devices may be removable or fixed, with fixed designs such as the band-and-loop appliance, lingual arch, and Nance appliance being widely used because of their reliability and favorable clinical outcomes [1,2].

Traditional fabrication of space maintainers involves several clinical and laboratory procedures, including dental impressions, cast fabrication, adjustment of metallic components, and appliance assembly. These steps may be challenging in pediatric patients because of limited cooperation and reduced tolerance for lengthy dental procedures. Moreover, inaccuracies introduced during impression taking or laboratory processing can accumulate and negatively affect the final fit and clinical performance of the appliance [1].

The rapid development of digital technologies over the past decade has substantially changed dental practice. The combination of intraoral scanning with computer-aided design and manufacturing (CAD/CAM) systems enables the production of customized appliances with high precision while reducing the number of clinical and laboratory stages. Digital workflows have been associated with improved treatment predictability, shorter working times, and greater patient comfort [1].

Three-dimensional (3D) printing, also known as additive manufacturing, has become an important component of modern digital dentistry. In contrast to subtractive techniques, where an object is created by removing material from a solid block, additive manufacturing builds structures layer by layer. This approach allows the production of complex geometries and individualized devices adapted to each patient's anatomical and functional requirements [1].

Among the additive manufacturing technologies used in dentistry, stereolithography (SLA), digital light processing (DLP), and liquid crystal display (LCD) printing are the most common. These methods employ light-curable resins that are polymerized in successive layers through controlled light exposure. The mechanical characteristics of the printed structures are influenced by multiple factors, including material composition, printing orientation, layer thickness, degree of polymerization, and post-curing procedures [1-8].

Advances in photopolymer materials have expanded the applications of 3D printing from diagnostic models and surgical guides to temporary restorations, orthodontic appliances, and prosthetic devices. Contemporary hybrid resins contain inorganic

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filler particles dispersed within a polymer matrix, improving both mechanical properties and dimensional stability. NextDent C&B Micro Filled Hybrid is one such material, developed for the fabrication of temporary restorations and other dental applications using 3D-printing technology [3,8].

An important aspect of additive manufacturing is that the mechanical behavior of a structure depends not only on the material used but also on its geometric design. Device geometry has a substantial influence on stress distribution, structural rigidity, and crack propagation patterns. Relatively small changes in thickness, connector dimensions, or reinforcement features may result in significant differences in load-bearing capacity and fracture behavior [7,8].

This relationship between geometry and mechanical performance is particularly relevant in digital dentistry because CAD software allows precise control of design parameters. Consequently, optimizing appliance geometry may provide an effective means of improving structural strength without increasing appliance size or changing the material employed [7,8].

Interest in the use of 3D printing for the fabrication of space maintainers has grown considerably in recent years. In their systematic review, Zarean and colleagues concluded that digital manufacturing technologies represent a promising alternative to conventional methods, offering advantages in customization and workflow efficiency. Nevertheless, they emphasized the need for additional research regarding the mechanical properties and clinical performance of additively manufactured devices [1].

Watson and co-workers reported that both stress distribution and structural resistance of 3D-printed space maintainers are strongly affected by appliance design. Their findings demonstrated fracture-load values suitable for clinical application and suggested that geometric optimization may enhance mechanical performance [4].

Similar results were obtained by Aktaş and Atabek, who showed that both the selected material and the structural configuration of the appliance significantly influence the fracture resistance of 3D-printed space maintainers [5].

More recent randomized clinical studies have confirmed the feasibility of manufacturing space maintainers through fully digital workflows, highlighting benefits related to individualized fit and favorable clinical outcomes of 3D-printed devices [6].

Despite the progress achieved in recent years, available evidence regarding the relationship between CAD design and the mechanical behavior of LCD 3D-printed space maintainers remains limited. Most investigations have focused on material characteristics or clinical applicability, whereas the influence of geometric modifications on structural strength has received comparatively less attention [1,4,5].

In light of these considerations, the present study aimed to evaluate the influence of design on the mechanical behavior of space maintainers fabricated by LCD 3D printing using NextDent C&B Micro Filled Hybrid resin. The specific objective was to assess the effect of CAD design on compressive strength and structural failure patterns by comparing two design configurations subjected to

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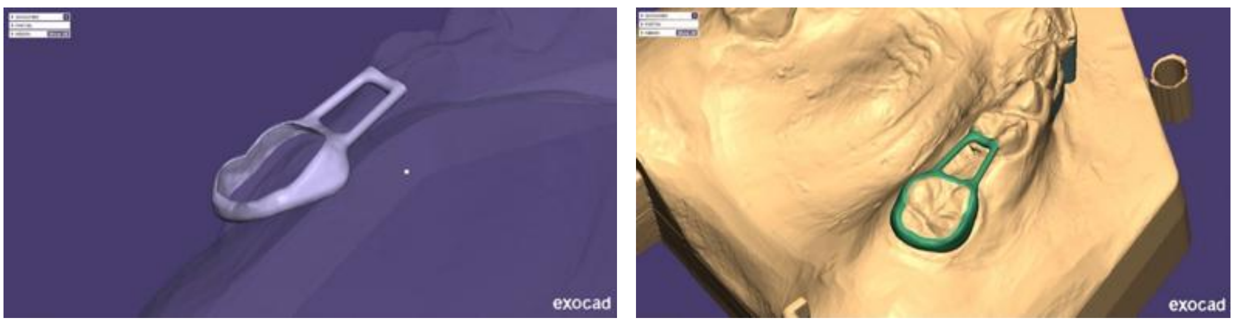
mechanical testing with a Zwick/Roell Z007 universal testing machine.

2. Materials and method

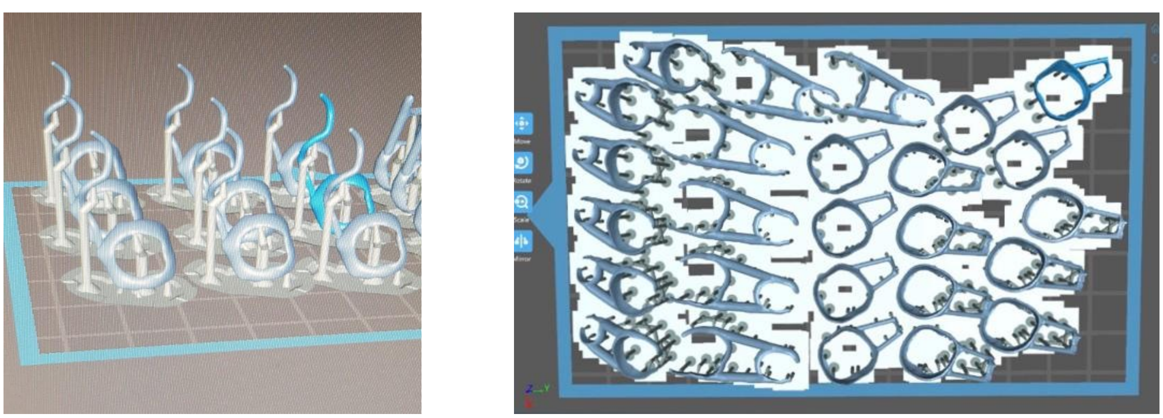
This in-vitro experimental study was conducted to investigate the effect of appliance design on the mechanical performance of space maintainers manufactured by LCD 3D printing using the photopolymer resin NextDent C&B Micro Filled Hybrid.

Three design configurations were evaluated. Group G1 (Standard Digital Design) consisted of a model obtained from an online 3D design library, while Groups G2 (CAD Design A) and G3 (CAD Design B) were custom-designed using Exocad software (Exocad GmbH, Germany) Fig.1- a,b. The only variable that differed among the groups was the geometric design of the appliances; all other manufacturing and testing conditions were standardized.



(a) (b)

Figure 1. (a) Digital model of the G2 space maintainer (CAD Design A) designed using Exocad software. The design was developed to replace a prematurely lost primary molar and consists of a retention band and a space-maintaining arm. The resulting STL file was used for additive manufacturing by means of LCD 3D printing; (b) Virtual adaptation of the G2 space maintainer on the digital dental arch model in the Exocad environment, used to verify its positioning, relationship with adjacent teeth, and overall dimensions prior to STL file export.



(a) (b)

Figure 2. STL files of the evaluated space maintainer designs. (a) Standard Digital Design. (b) The G2 design (left) represents the initial configuration, whereas the G3 design (right) incorporates additional structural reinforcements and increased thickness in areas prone to fracture, aiming to optimize the mechanical performance of the device.

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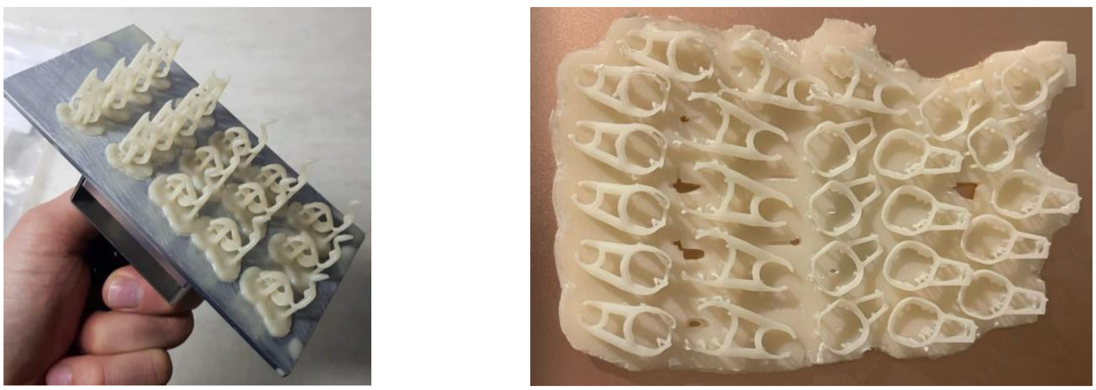
The designs were exported as STL files and prepared for production using Chitubox software (versions 1.7 and 1.9). All specimens were fabricated with a Phrozen Sonic Mini 4K printer (Phrozen Technology, Taiwan) employing LCD-based vat photopolymerization technology (Fig 2 a,b).

Printing parameters were identical for all groups and included a layer thickness of 0.05 mm, four initial layers, an exposure time of 8 seconds for regular layers and 45 seconds for the initial layers, a lifting distance of 4 mm, a lifting speed of 50 mm/min, and a retract speed of 120 mm/min. Each model was positioned at an angle of approximately 30–45° relative to the build platform, and support structures were generated to ensure stability during fabrication.

The material selected for this study was NextDent C&B Micro Filled Hybrid resin (NextDent B.V., The Netherlands), a photopolymer specifically developed for dental applications manufactured through 3D printing (Fig. 3 – a,b).



(a) (b)

Figure 3. Fabrication assemblies ("print jobs") of the 3D-printed space maintainers manufactured from NextDent C&B Micro Filled Hybrid resin. The specimens are presented immediately after LCD 3D printing and prior to washing, support removal, and post-curing, illustrating the build orientation and support structures used during fabrication. (a) Comparison between the Standard Digital Design (G1) and CAD Design B (G3). (b) Comparison between CAD Design A (G2) and CAD Design B (G3), the two customized designs included in the mechanical testing protocol. After printing, all support structures were removed and the specimens were rinsed in isopropyl alcohol to eliminate residual uncured resin. A post-curing procedure using ultraviolet light was subsequently performed according to the manufacturer's instructions.

The mechanical behavior of the space maintainers was evaluated by compression testing using a Zwick/Roell Z005 universal testing machine (ZwickRoell GmbH, Germany). Each specimen was mounted on a supporting model, and an axial load was applied through a vertical metallic loading rod until structural failure occurred Fig. 4 – a,b. The maximum load sustained before fracture or permanent deformation was recorded for each specimen and expressed in Newtons (N).

All specimens belonging to Group G1 exhibited premature fracture before mechanical testing could be completed. Consequently, this group was excluded from the statistical analysis, and only Groups G2 and G3 were included in the final evaluation.

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(a)

(b)

Figure 4. (a) Mechanical compression testing performed using the Zwick/Roell Z005 universal testing machine. (b) Detailed view of the experimental setup, showing the positioning of the space maintainer on the supporting model and the application of axial load through the loading rod during the compression test.

3. Statistical analysis

Statistical processing was performed using IBM SPSS Statistics software (version 26; IBM Corp., Armonk, NY, USA). Descriptive statistics were calculated for each experimental group, including mean values, standard deviations, standard errors, and minimum and maximum measurements.

Data distribution was assessed using the Shapiro–Wilk test, while homogeneity of variances was examined with Levene's test. Because all specimens in Group G1 fractured before testing and could not be analyzed quantitatively, statistical comparisons were limited to Groups G2 and G3.

Differences between the two groups were examined using the independent-samples Student's t-test. Statistical significance was established at a threshold of $p < 0.05$. Results are presented as mean ± standard deviation (SD).

4. Results

All specimens assigned to Group G1 (Standard Digital Design) experienced structural failure during handling or positioning prior to mechanical testing. Because fracture occurred before load application, fracture-strength measurements could not be obtained for this group, and it was therefore excluded from further statistical evaluation.

Maximum fracture-load values (N) were recorded for Groups G2 (CAD Design A) and G3 (CAD Design B). Group G3 demonstrated substantially greater resistance to compressive loading than Group G2, with mean fracture loads of 94.40 ± 13.63 N and 52.32 ± 17.55 N, respectively (Table 1, Fig. 5).

Assessment of the statistical assumptions confirmed that the data were normally distributed in both groups, as indicated by the Shapiro–Wilk test ($p > 0.05$). Variance homogeneity was also verified using Levene's test ($p = 0.506$). Examination of the boxplots

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did not identify any outlying observations Fig.6.

Comparison of the two design configurations using an independent-samples Student's t-test revealed a statistically significant difference between the groups ($t(12) = -5.01$, $p = 0.0003$), as shown in Table 2. Group G3 exhibited significantly higher fracture loads than Group G2, with a mean difference of 42.08 N (95% CI: 23.78–60.39 N). The effect size was large (Cohen's d = 2.68).

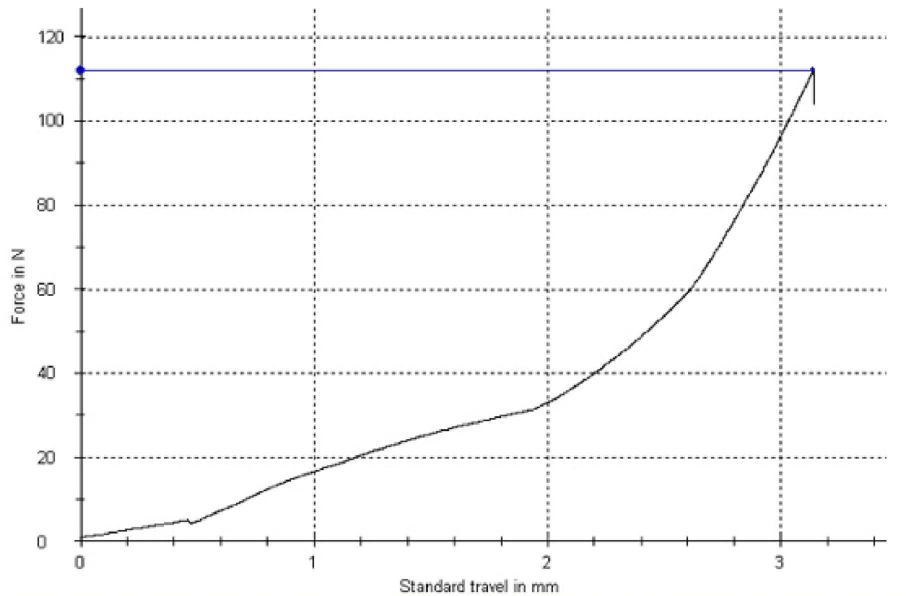

Figure 5. Representative load–displacement curve recorded during compression testing of the G3 (CAD Design B) specimen showing the highest load at failure.

Table 1. Descriptive statistics of fracture-load values.

Group	Mean (N)	SD	SE	Minimum	Maximum
G2 – CAD Design A	52.32	17.55	6.63	30.84	76.52
G3 – CAD Design B	94.40	13.63	5.15	75.87	112.60

Table 2. Results of the independent-samples t-test.

Parameter	Value
t	−5.01
Degrees of freedom (df)	12
p value	0.0003
Levene’s test (p)	0.506

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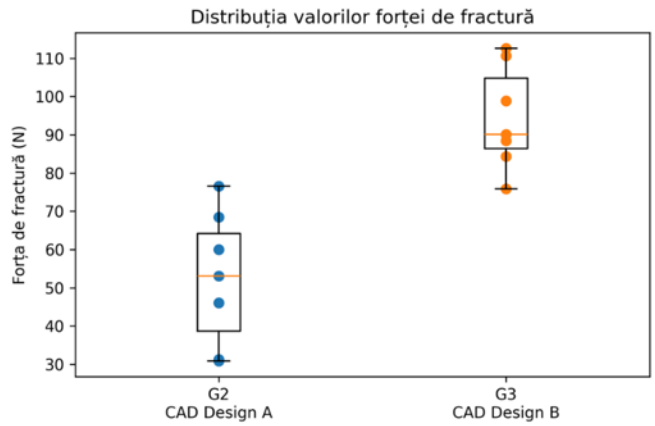

Figure 6. Distribution of fracture-load values for Groups G2 (CAD Design A) and G3 (CAD Design B). The boxplot displays the median, interquartile range, and extreme values, while the individual points correspond to the measurements obtained from each specimen. Group G3 demonstrated significantly higher fracture-load values than Group G2 ($t(12) = -5.01$, $p = 0.0003$).

5. Discussion

The findings of the present investigation indicate that geometric design plays a decisive role in the mechanical performance of space maintainers fabricated by LCD 3D printing using NextDent C&B Micro Filled Hybrid resin. Among the three configurations evaluated, the standard model obtained from a digital library (G1) failed before mechanical testing could be completed, whereas both custom-designed CAD models remained intact and were successfully tested. Furthermore, the two CAD designs exhibited markedly different fracture-load values. These observations suggest that the structural behavior of additively manufactured appliances depends not only on the material itself but also on the way the device is designed and reinforced [4,5].

The present results are consistent with current knowledge regarding additive manufacturing in dentistry, where mechanical performance is known to be influenced by a combination of material characteristics, printing conditions, and geometric design. One of the major advantages of digital manufacturing is the possibility of modifying the geometry of a device to improve stress distribution and structural efficiency without altering the material composition [9].

In the current study, Group G3 demonstrated a mean fracture load of 94.40 N, considerably higher than the value recorded for Group G2 (52.32 N). This substantial difference indicates that the geometric modifications incorporated into CAD Design B improved the ability of the structure to withstand applied loads. A more favorable distribution of stresses throughout the appliance may have reduced the formation of localized stress concentrations, thereby increasing resistance to fracture. Such behavior is consistent with established principles of structural mechanics, according to which geometry directly affects stiffness, load transfer, and failure patterns in additively manufactured components [7].

The development of CAD Design B was guided by observations made during the

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preliminary design and testing phases. Early evaluations revealed that the most vulnerable regions were located at the arms of the space maintainer and the distal portion of the retention ring. In these areas, limited material thickness appeared to create structural weak points that were more susceptible to stress accumulation and mechanical failure. To address this issue, modifications were introduced to increase rigidity in these critical regions and promote a more uniform transfer of forces throughout the appliance. The significantly higher fracture resistance observed in Group G3 suggests that these design adjustments effectively enhanced structural integrity and reduced the likelihood of failure under loading conditions [7].

Particular attention should be given to the behavior of Group G1, which could not be included in the mechanical evaluation because all specimens fractured before testing. This finding highlights a potential limitation of standard designs available in online digital libraries. Although such models are easily accessible and can simplify the fabrication process, they may not be optimized to withstand the biomechanical demands encountered in clinical use. The fractures observed in this group occurred primarily in regions characterized by reduced cross-sectional dimensions and insufficient reinforcement. These findings contributed directly to the development of the customized CAD designs assessed in the present study and emphasize the importance of biomechanical validation before clinical implementation of pre-existing digital models [4].

The resin used in this investigation, NextDent C&B Micro Filled Hybrid, is widely employed in dental additive manufacturing applications. Previous studies have shown that the mechanical performance of printed dental resins can be affected by factors such as printing orientation and layer thickness, indicating that manufacturing parameters may substantially alter the final strength of printed structures [10].

To minimize the influence of such variables, all specimens in the present study were fabricated under identical conditions. Printing orientation, layer thickness, and post-curing procedures were standardized for every group. As a result, the differences observed between the tested designs can reasonably be attributed primarily to variations in CAD geometry rather than to manufacturing-related factors, supporting the central hypothesis of the study [10].

From a clinical perspective, the higher fracture-load values recorded for Group G3 suggest a greater capacity to tolerate functional forces compared with Group G2. Although masticatory forces in the primary dentition are generally lower than those observed in adults, space maintainers remain in service for extended periods and are continuously exposed to repeated loads generated by mastication, swallowing, and parafunctional habits. Therefore, improving the mechanical strength of these appliances may contribute to a lower risk of fracture and potentially enhance their long-term clinical durability [5,6].

Nevertheless, the results should be interpreted within the limitations of the experimental design. The mechanical assessment performed in this study was restricted to static compression testing. In the oral environment, dental appliances are subjected to multidirectional and cyclic

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loading, as well as fluctuations in temperature, humidity, and pH. Consequently, laboratory findings cannot be directly translated into clinical performance without careful consideration of these additional factors [5,9].

Several limitations should be acknowledged. The study included a relatively small number of specimens, evaluated only one printable resin, and employed a single printing and post-processing protocol. In addition, factors such as artificial aging, thermal cycling, and fatigue loading were not investigated, despite their potential influence on the long-term behavior of photopolymer materials used in dentistry [10].

Within the limitations of this study, the results demonstrate that CAD design optimization is a critical determinant of the mechanical performance of LCD 3D-printed space maintainers. Among the evaluated configurations, CAD Design B exhibited the highest resistance to fracture, suggesting that targeted geometric modifications in structurally vulnerable regions may represent an effective approach for developing customized space maintainers with improved biomechanical performance and enhanced clinical reliability [4,5,9].

6. Conclusions

The findings of this study indicate that CAD design is a critical factor influencing the mechanical performance of space maintainers manufactured through LCD 3D printing using NextDent C&B Micro Filled Hybrid resin. Among the evaluated designs, CAD Design B exhibited significantly greater fracture resistance than CAD Design A, whereas the standard digital model lacked sufficient structural integrity to withstand testing. These observations suggest that geometric optimization plays a fundamental role in determining the biomechanical behavior of additively manufactured space maintainers.

The results support the application of customized digital design strategies in the development of 3D-printed space maintainers and highlight the importance of further research aimed at assessing their performance under clinical conditions and prolonged functional loading.

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Author contributions

Authors read and approved the final manuscript. All authors have equally contributed to this work.

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Conflict of interest statement

The authors declare no conflicts of interest concerning this study.

Data availability statement

Will be provided on request.

Ethics statement

The study was approved by the Ethics Committee of the Victor Babes University of Medicine and Pharmacy of Timisoara, no. 121/2022 rev 07.04.2026.

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