Fracture Resistance of Space Maintainers Produced Using 3D Printable Materials

N. Aktaş, D. Atabek

Department of Pediatric Dentistry, Faculty of Dentistry, Gazi University, Ankara, Türkiye

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Email: nagehanaktas@gazi.edu.tr

Abstract

Aim This study aimed to evaluate the fracture resistance of space maintainers (SMs) produced using 3D-printable materials (metal, resin and polyetheretherketone [PEEK]) after thermal aging and compare them with conventional space maintainers.

Methods A standardised typodont model for paediatric dentistry was utilised, and band and loop space maintainers were designed digitally using computer-aided design (CAD) technology. Four groups were established: Conventional, 3D printed metal, 3D printed resin, and 3D printed PEEK. Fracture resistance was assessed after 10,000 thermal cycles, simulating oral conditions. Fracture tests were conducted using a universal testing machine, applying vertical force to the band and loop junction until fracture. Statistical analyses were performed using one-way ANOVA and the Tukey HSD test ($P<0.05$).

Results 3D printed metal SMs showed the highest maximum loading force with 922.35 ± 145.43 N. ($p<0.001$). The maximum loading force for the 3D printed PEEK, conventional, and 3D printed resin groups were 262.34 ± 41.50 N, 188.86 ± 63.40 N, and 183.99 ± 84.41 N, respectively. There was no significant difference between the three groups (PEEK, conventional, and resin group) ($p>0.05$).

Conclusion Although the fracture resistance values showed that metal, resin, and PEEK 3D printed band and loop space maintainers can be acceptable clinically, the permanent resin may be preferable to printable material because of their aesthetic properties.

KEYWORDS 3D printing; 3D printed resin; Digital space maintainers; Paediatric dentistry; Polyetheretherketone.

Introduction

Preserving primary teeth until normal exfoliation is a crucial aspect of paediatric dentistry. Beyond their aesthetic, speech, and mastication functions, primary teeth play a vital role in guiding and facilitating the eruption of permanent teeth. When early loss of primary teeth occurs, space maintainers (SMs), which help prevent the loss of arch length and width, are recommended as an essential aspect of preventive orthodontics [American Academy of Pediatric Dentistry, 2016; Zarean et al., 2023]. The conventional band and loop SMs are commonly used to preserve the space resulting from the unilateral loss of a single primary molar [Khanna et al., 2021]. Although the band and loop SMs have high survival rates and good patient compatibility, they have some disadvantages [Tokuc and Yilmaz, 2022]. Cement loss, inadequate band pinching, solder breakage, and metal components impinging on the soft tissue were common complications of SMs [Ahmad et al., 2018]. Recently, digital technology has been used as an alternative to the conventional band and loop SMs and to overcome their disadvantages [Soni, 2017; Pawar, 2019; Khanna et al., 2021; Rodrigues et al., 2024; Lee et al., 2023].

Computer-aided design and computer-aided manufacturing (CAD-CAM) technologies have significantly developed in dentistry in recent years. This progression has been marked by the evolution of materials and the digitalisation and automation of various work processes [Campobasso et al., 2023]. CAD-CAM technologies using subtractive manufacturing (milling technology) and additive manufacturing (3D printing technology) methods may be helpful in the predictability of oral rehabilitation by eliminating extensive laboratory procedures and human-based errors, with advantages over conventional techniques, including lower cost, less chairside time and patient compliance [Khanna et al., 2021, Dhanotra and Bhatia, 2021, Rodrigues et al., 2024]. The milling technology has been successfully used to fabricate space maintainers from zirconia and polymethylmethacrylate (PMMA) [Soni, 2017; Rodrigues et al., 2024; Lee et al., 2023]. The applications of 3D printing in dentistry have gained significant attention in the last few years as they are expected to change the future of health care and have expanded rapidly to include several areas [Balhaddad et al., 2023]. 3D printing technology has also been used for the fabrication of space maintainers in paediatric dentistry. In their case reports, Pawar [2019] and Khanna et al. [2021] utilised 3D printer technology to fabricate space maintainers using a titanium-based powdered metal material. They reported that 3D printed space maintainers ensure maximum precision with the least

Product	Printing Technique	Content	Manufacturer
Cobalt-Chromium (Co-Cr) dental alloy powder	SLS	63,9% Co, 24,7% Cr, W 5,4%, Mo 5,0%, Si 1.0%, C,Fe,Mn, N <1.0%	Scheftner Dental Alloys, S&S Scheftner GmbH, Mainz, Germany
Permanent Crown Resin (Methacrylic acid ester-based resin	SLA	Organic Matrix: 50-<75% wt. Bis-EMA Esterification products of 4.4'-isopropylidiphenol, ethoxylated and 2-methylprop-2enoic acid. Silanized dental glass, methyl benzoylformate, diphenyl [2,4,6-trimethylbenzoyl] phosphine oxide. Inorganic Filler: Silanized dental glass (particle size 0.7µm) (30-50% wt.)	Formlabs Inc., Somerville, MA, USA
VESTAKEEP® PEEK	FDM	Polyetheretherketone, is polycondensed from the building blocks hydrochinone and 4,4´-difluorobenzophenone.	Daicel-Evonik, Tokyo, Japan

TABLE 1 3D printable material used in the study.

possible defects than conventional band and loop space maintainers. There has been a growing demand for metal-free materials in modern paediatric dentistry because of aesthetic considerations and the potential complications associated with metal allergies [Maekawa et al., 2015]. Recently, permanent resins for 3D printers from different companies have been introduced to the market for long-term use in the oral cavity [Vichi et al., 2023, Nam et al., 2024]. Resin materials represent an aesthetic, durable, and cost-effective alternative for restoring primary molar teeth [Kim et al., 2022]. Additionally, it has been reported that resins can be used to print appliances such as space maintainers [Pawar, 2019; Tsolakis et al., 2022]. Watson et al. [2023] designed, fabricated, and evaluated in vitro 3D printed space maintainers using different light-cured resin materials. The use of new polymers (metal-free) such as polyetheretherketone (PEEK) has been proposed as a viable alternative to conventional materials, offering clinicians the possibility of customised 3D printing [Beretta et al., 2021; Tsolakis et al., 2022]. PEEK is a high-performance polymer with high biocompatibility, good mechanical properties, high-temperature resistance, low plaque affinity, and high bond strength [Guo et al., 2020]. PEEK has been found to have ideal chemical-physical features that allow their use in orthodontics. This material is biocompatible with excellent physical and mechanical properties [Beretta et al., 2021; Paglia et al., 2022]. The researchers utilised milling technology to fabricate removable space maintainers from PEEK materials, finding PEEK to be a highly suitable material for manufacturing space maintainers [Ierrardo et al., 2017; Guo et al., 2020].

However, there have not been any reports of using 3D printing technology to manufacture band and loop space maintainers from long-term permanent resin and PEEK materials. The aim of this study is to evaluate the fracture resistance of in-vitro 3D printed metal, resin, and PEEK space maintainers after thermal aging and to compare them with conventional SMs. The null hypothesis of the present study was that there are no significant differences among the various groups tested in fracture resistance

Methods

Study design

The minimum sample size was calculated with a large effect size (f=0.40), 0.05 type 1 error value, and 0.85 power value. Accordingly, the minimum sample size for each group was calculated (G power ver.3.1.9.4) and found as 15.

A standard typodont model for paediatric dentistry (AK-6/2M, Frasaco, Tettnang, Germany) was used. The mandibular primary first molar tooth was removed in this model, and thus, a partial-defect dentition model was created for band and loop space maintainer design. This model was scanned using a desktop 3D scanner (3Shape E1, 3Shape A/S, Denmark), and a virtual model was created. Then, the images of the virtual models were converted to a Standard Tessellation Language (STL) file. This STL file was transferred to dental design software (Exocad DentalCAD 2.2 Valetta; Exocad GmbH). The band and loop space maintainer were designed similarly to the conventional space maintainer on the virtual model. The digital design of the space maintainer had 0.6 mm of band thickness, 1.5 mm of loop thickness, 7 mm of length of the loop, and 0.06 mm of cement space (Figure 1). The same STL file was used to fabricate metal, resin, and PEEK band and loop space maintainers using 3D printing technology. The properties of the 3D printable materials are presented in Table 1.

Group 1 (Conventional): Resin models were manufactured using a light-cured model resin (Formlabs, Sommerville, Massachusetts, USA) and 3D printer (Formlabs Form 3B+, Sommerville, Massachusetts, USA) to fabricate conventional band and loop space maintainers. The suitable prefabricated stainless steel molar band (3M Unitek, Monrovia, CA, USA) was selected according to the size of the abutment tooth (mandibular primary second molar tooth) on the resin models. A cantilevered loop of stainless-steel wire is soldered to a prefabricated band.

Group 2 (3D-printed metal): The 3D printed metal band and loop space maintainers were fabricated using an STL file through selective laser sintering (HBD-100, Shanghai Hanbang, China). Space maintainers were manufactured with a 30-micron layer thickness using Cobalt-Chromium (Co-Cr) dental alloy powder material (Scheftner Dental Alloys, S&S Scheftner GmbH, Mainz, Germany).

Group 3 (3D-printed resin): For the fabrication of the 3D-printed resin band and loop space maintainers STL file was transferred into a software (PreForm; Formlabs, Sommerville, Massachusetts, USA). Resin band and loop space maintainers were printed using permanent crown resin (Formlabs) with a dental 3D-printer Formlabs Form 3B (Formlabs). After printing, post-processing was applied to the samples in line with the manufacturer's recommendations. After printing, the specimens underwent a cleaning procedure

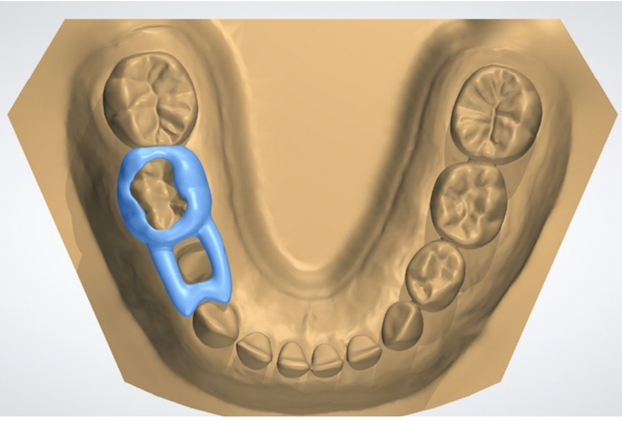

FIG. 1 The digital design of 3D printed band and loop space maintainers.

employing FormWash (Formlabs) to eliminate residual uncured resin. Then, the specimens underwent a post-curing step, for 20 minutes at 60 °C within the FormCure device (Formlabs).

Group 4 (3D-printed PEEK): The 3D-printed PEEK band and loop space maintainers were fabricated polyetheretherketone filament (VESTAKEEP® PEEK, Daicel-Evonik, Tokyo, Japan) with Apium M220 3D Printer (Apium Additive Tech GmbH, Germany) using STL file.

Thermocycling and fracture test

Ten thousand thermal cycles were subjected to all specimens in 5 °C - 55 °C water baths for 30 seconds dwell time in a thermocycling device (Thermocycler THE 1100, SD Mechatronic GMBH, Germany) in distilled water. Then, the specimens were embedded in polyethylene pipes upright using a self-curing acrylic material (Panacryl; Ruby Dent, Istanbul, Turkey) from the band portion and 2 mm below the band-loop junction.

The specimens (n=60) were fixed on the universal test machine (LLYOD, Llyod Instruments Ltd., UK). The load was vertically applied to the band and loop junction of the sample with a steel ball (5 mm in diameter) at a crosshead speed of 0.5 mm/min until the fracture, and the load at fracture (N) was recorded as fracture resistance for each specimen. Fractures were determined through audio or mechanical detection during loading.

Statistical analyses

Statistical analyses were performed using a statistical software program (SPSS 23.0, IBM Corp., NY, USA). The normalities of the data were tested with the Shapiro-Wilk test. One-way ANOVA statistically analysed the data for maximum loading force, followed by multiple comparisons by the Tukey HSD test. Results were considered statistically significant for *P*<0.05.

Results

The mean fracture resistance values and their standard deviations of the experimental groups were shown in Table 2. The 3D printed metal group showed the highest maximum loading force with 922.35 ± 145.43 N. In the 3D-printed metal group, the fracture resistance values were significantly different compared to the other groups (p<0.05). The lower fracture resistance values were observed in the 3D-printed resin group with 183.99 ± 84.41 N. The maximum loading force for the 3D-printed PEEK, conventional, and 3D-printed resin groups were 262.34 ± 41.50 N, 188.86 ± 63.40 N, and 183.99 ± 84.41 N, respectively, and there was no significant difference between the three groups (p>0.05).

Discussion

In the present study, the fracture resistance of SMs produced using different 3D printing materials was assessed. The null hypothesis of the study was that there would be no significant differences in the fracture resistance of SMs produced using the 3D printing method and materials. The results showed that 3D printed materials were effective on the fracture resistance values. In the present study, the null hypothesis was rejected as there was a significant difference between the various groups tested in terms of fracture resistance.

The conventional band and loop space maintainers are fabricated by a cantilevered loop of stainless-steel wire soldered to a prefabricated band. Due to its cantilever design, functional loading of the cantilever loop may lead to solder breakages during usage, resulting in the appliance's clinical failure and soft tissue problems [Kara et al., 2013]. It has been reported that 3D printers allow space maintainers to be printed as a single unit, thus minimising the breakage of space maintainers and reducing appliance failure [Pawar, 2019, Khanna et al., 2021]. Therefore, in this study, the use of 3D printing technology in space maintainers' production is evaluated to overcome the problems associated with traditional manufacturing.

3D-printed technologies have gained popularity and become preferred as alternatives to conventional applications. However, it is worth noting that the use of these systems in paediatric dentistry is still limited. 3D printing has found use in the creation of space maintainers and various orthodontic

Group	Mean ± standard deviation	(minimum – maximum)		P value
Conventional	188,86 ± 63,40a	98,10 - 305,26		<0.001
3D Metal	922,35 ± 145,43b	746,11 - 1260,68		
3D Resin	183,99 ± 84,41a	82,31 - 336,07		
3D PEEK	262,34 ± 41,50a	208,21 -337,25		

**Same superscript lowercase letters indicate that there is no significant difference between the groups (P>0.05).*

TABLE 2 Descriptive statistics of the fracture resistance values (N).

appliances, including brackets and clear aligners. It has been reported that 3D printing applications will significantly benefit the fields of paediatric and early orthodontic applications [Campobasso et al., 2023; Aksoy et al., 2023]. The number of studies investigating using 3D printing technology in manufacturing SMs is limited in paediatric dentistry. The existing studies have reported various methodologies, materials, and technologies [Pawar, 2019, Khanna et al., 2021, Watson et al., 2023]. To the best of the authors' knowledge, there is no existing study regarding the fracture resistance of 3D printed metal, permanent resin, and PEEK SMs.

Fracture resistance is one of the main properties defining dental materials' mechanical behaviour. Evaluation of the fracture resistance of a dental material is essential to predict its clinical durability. Although the SMs serve for a short time in the mouth until the permanent tooth eruption, the material must provide suitable mechanical properties in the oral environment for clinical success. It has been reported that chewing hard food and the eruption of opposing teeth may cause the fracture of the loop due to increased mechanical stress on the loop [Ahmad et al., 2018]. This study evaluated the fracture strength of the 3D printing band and loop SMs by applying force to the band and loop junction.

Fracture resistance may be affected by the change in printed material and the printer type in 3D printing technology [Aksoy et al., 2023]. There are several additive manufacturing methods using different printing techniques. Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), Stereolithography (SLA), and Digital Light Processing (DLP) are the common 3D printing methods in dentistry. SLS involves the layer-by-layer laser fusion of powdered metal material until the desired object takes shape. In FDM, heated materials are extruded as molten droplets, which solidify upon deposition, layer by layer, ultimately forming the intended object. SLA is the most popular 3D printing method in dentistry, and in this method, the material deposits in light photosensitive layers and polymerises to form the printed structure [Balhaddad et al., 2023; Aksoy et al., 2023]. Due to their small size and user-friendly nature, SLA printers can be installed in dental offices. Conversely, due to their enormous size and the specialised machinery required for post-printing procedures, SLS printers for metal printing are impractical within the office setting [Tsolakis et al., 2022]. In this study, metal 3D-printed SMs were produced using SLS technology, resin 3D-printed SMs were produced SLA technology, and PEEK 3D-printed SMs were produced using FDM technology.

Comparing the groups' fracture loads revealed that the 3D metal band and loop space maintainers showed significantly higher fracture resistance than other space maintainers ($p<0.05$). The maximum loading force for the 3D metal group was 922,35 ± 145,43 N. The materials for metal 3D printing are limited mainly to cobaltium-chromium (CoCr) and titanium. Pawar [2019] and Khanna et al. [2021] used SLS technology to fabricate band and loop space maintainers using a titanium-based powdered material. Tokuc and Yilmaz [2022] evaluated the band fit of metal 3D printed SMs using SLS technology. They reported no significant differences in the fit of the conventional and 3D-printed metal band and loop space maintainers. Although SMs produced from metal 3D printable materials such as CoCr and titanium alloys seem suitable for clinical use; these materials have been reported to be hard, non-flexible, and unaesthetic [Tsolakis et al., 2022, Zarean et al., 2023]. For the metal band and loop limitations to be efficiently overcome, the authors reported that the tooth-colored space maintainers were produced using milling technology [Soni, 2017]. Rodrigues et al. [2024] and Lee et al. [2023] reported a digital workflow for manufacturing CAD-CAM space maintainers, have satisfactory adaptation, aesthetics, and strength, from zirconia and polymethylmethacrylate (PMMA). Milling is not used in creating paedodontic and orthodontic appliances mainly due to the excessive loss of material and the complexity of these appliances. Nowadays, 3D printing is the main way to manufacture all kinds of these appliances, such as SMs, bands, brackets [Tsolakis et al., 2022]. Watson et al. [2023] evaluated the retentive capability of 3D printed SMs using different clear resin materials to produce clear aligners and splints. They reported that strength under the load of claw-design 3D printed space maintainers may be adequate as a viable alternative to traditional SMs. In this study, permanent crown resins were used to produce aesthetic SMs. The fracture resistance values of 3D resin SMs were 183.99 ± 84.41 N, and these values were not significantly different from the conventional group ($p>0.05$). Kim et al. [2022] used temporary crown resin to produce aesthetic primary molar restorations and concluded that 3D printed resin crowns are resistant to occlusal forces and can be used as an alternative for primary teeth. Ierrardo et al. [2017] utilised milling technology to fabricate removable space maintainers from PEEK materials, finding PEEK to be highly suitable for manufacturing space maintainers. Guo et al. [2020] reported that the mucosal fit of the CAD/CAM-fabricated removable space maintainers from PEEK materials was superior to conventional removable space maintainers. The fracture resistance values of 3D PEEK SMs were 262.34 ± 41.50 N, and which were not significantly different from conventional and 3D resin groups ($p>0.05$). This study is the first original research about the fracture strength of 3D-printed and conventional band and loop space maintainers. Therefore, there are no similar studies where the results can be compared. Similar fracture resistance to conventional space maintainers shows that these materials are may suitable for manufacturing band and loop space maintainers. Although the mechanical properties of the 3D-printable PEEK material are at the desired level, there is a need to improve the esthetic properties.

This study focused on evaluating the fracture resistance of SMs produced using 3D printing technology. It is well-known that fracture is the main cause of failure of restorations because of aging with thermal changes and cyclic loads in the oral cavity. Reymus et al. [2020] reported reduced fracture load values after artificial aging for resin 3D printed materials, which may limit their clinical use. Therefore, evaluating the mechanical properties of restorative materials after aging is useful to predict their clinical performance. The tested specimens were subjected to 10,000 thermal cycles, which is approximately 1 year of intraoral aging [Gale and Darvell, 1999]. Braun et al. [1999] reported that the maximum bite force was 78 N at 6 to 8 years. Another study reported that the maximum bite force was 176 N in the early primary dentition [Gale and Darvell, 1999]. The fracture strength is approximately determined by the mechanical strength of the material as well as its rigidity [Alp et al., 2022]. For this reason, high fracture resistance, especially in the 3D metal group, increases the hardness of the material. Therefore, occlusal alignment is essential when designing and using the space maintainers, so the stress on the abutment tooth must be considered. 3D-printed space maintainers have a fine adaptation that does not prevent occlusion, even in high occlusal force situations.

The present study had some limitations. One of the limitations of this study was that the in vitro nature of the experiments limited the simulation of different intraoral conditions. In clinical practice, occlusal forces acting on the solder joint could be cited as the underlying cause for the early deterioration in the conventional band and loop space maintainer. Since the design of 3D-printed space maintainers allows for single-unit fabrications, the occlusal stresses were not transferred on the band in 3D-printed space maintainers [Tokuc and Yilmaz, 2022]. Finite element analyses can be performed to evaluate the mechanical behavior of the material under structural conditions.

The second limitation was the use of a single, standardised model, insufficient to mimic different clinical conditions. However, in this study, with the aim of standardized specimen preparation, dental study models for paediatric dentistry were used. Additionally, the cementation procedure was not used in the presented study. However, cement material is also one of the important factors affecting the clinical performance of space maintainers. The most appropriate approach for the cementation of 3D-printed space maintainers, whether traditional cementation materials or new materials such as bioactive cements, should be thoroughly investigated in future studies [Beretta et al., 2022, Beratta et al., 2023].

The advancement of technology in the developing world necessitates using newer and modern equipment instead of conventional treatments in clinical practice. This research has combined digitalisation technology and the clinical requirements of paediatric dentistry. The comparable mechanical properties of the 3D space maintainers indicate that they may have the potential for use in paediatric dentistry. Although the fracture resistance values showed that metal, resin, and PEEK 3D printed band and loop space maintainers can be clinically acceptable, the permanent resin may be preferable printable because of its aesthetic properties. More studies are needed to evaluate the long-term clinical performance and to determine their optimal design and manufacturing parameters.

Conclusion

- 3D printing technology stands out as a novel topic in paediatric dentistry with research potential. The 3D-printed space maintainers produced in this study may provide a basis for future clinical applications in paediatric dentistry.
- Using materials like PEEK and resin materials, combined with 3D printing, can produce high-quality, durable, and biocompatible space maintainers.
- The fracture strength has no significant difference between conventional, 3D printed PEEK, and 3D printed resin. More studies are needed to evaluate their optimal design and manufacturing parameters.

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