folia medica

Folia Medica 65(6):986-992
DOI: 10.3897/folmed.65.e107299

Original Article

Mechanical Properties of Materials for 3D Printed Orthodontic Retainers

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Received: 31 May 2023 ♦ **Accepted:** 24 Aug 2023 ♦ **Published:** 31 Dec 2023

Citation: Stoev YY, Uzunov TT, Stoyanova NS, Grozdanova-Uzunova RG, Kosturkov DN, Taneva IK. Mechanical properties of materials for 3D printed orthodontic retainers. Folia Med (Plovdiv) 2023;65(6):986-992. doi: 10.3897/folmed.65.e107299.

Abstract

Aim: The purpose of this study was to compare the mechanical properties of materials used for orthodontic retainers made by direct 3D printing and thermoforming.

Materials and methods: Twenty-one specimens (n=7) from 3 different materials (Formlabs Dental LT Clear V2 - Formlabs Inc., Somerville, Massachusetts, USA; NextDent Ortho Flex - Vertex-Dental B.V., Soesterberg, The Netherlands, and Erkodent Erkodur - ERKODENT, Germany) were manufactured and their mechanical properties were evaluated. Two of the specimen groups were 3D printed and the other one was fabricated using a material for thermoforming. The statistical methods we applied were descriptive statistics, the Kruskal-Wallis and Dunn's post-hoc tests.

Results: With respect to Young's modulus (E), the Kruskal-Wallis test (df=2, χ^2=17.121, p=0.0002) showed a significant difference between the materials for direct 3D printing of orthodontic retainers (E=2762.4 MPa±115.16 MPa for group 1 and 2393.05 MPa±158.13 MPa for group 2) and thermoforming foils (group 3, E=1939.4 MPa±74.18 MPa). Statistically significant differences were also found between the flexural strength (FS) (Kruskal-Wallis test, df=2, χ^2=17.818, p=0.0001) and F(max) (Kruskal-Wallis test, df=2, χ^2=17.818, p=0.0001).

Conclusions: The materials tested in the current study showed statistically significant differences in their Young's modulus, flexural strength, and F(max).

Keywords

retention, resin, orthodontics, thermoforming

INTRODUCTION

Retention after orthodontic treatment is a very important phase in the treatment that aims to keep teeth in their corrected positions.[1]

Retainers can be classified as either fixed or removable. The removable thermoformed type, which is the gold standard, is the most commonly used type of retainer by orthodontists.[2]

However, digital technology is transforming the orthodontic field. In comparison to thermoformed retainers, the new method for fabricating a 3D-printed removable retainer is more accurate and reliable.[3]

Polyethylene terephthalate-glycol (PETG), polyester, polyurethane, polypropylene, and polyethylene are currently the most common thermoplastic materials used to make orthodontic retainers. PETG has excellent mechanical properties, formability, and fatigue resistance, making it an

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important member of the rapidly expanding family of thermoplastic elastomers.[4] PETG is used to make the Erkodur foils investigated in this study. However, one of the negative results of the thermoplastic process is that there are significant changes in the material properties in response to the heat generation that forms the material around the teeth.[5] Studies have demonstrated that thermoplastic materials are reactive to the intraoral environment during their use. It has been shown that after storage in artificial saliva, the elastic modulus and tensile yield stress were modified, generally reducing the mechanical properties of the polymers for thermoforming.[5]

Dental LT Clear resin (Formlabs Inc., Somerville, Massachusetts, USA) is a class IIa biocompatible material and is a viable alternative, described in the literature for manufacturing aligners and retainers.[6] NextDent Ortho Flex (Vertex-Dental B.V., Soesterberg, The Netherlands) is also a clear biocompatible Class IIa material developed for 3D printed retainers and more.

Any dental material must have sufficient mechanical integrity to function in the oral cavity for an extended period.[7] The strength is still the most important criterion and can be determined by various experimental setups. Flexural testing can be conducted using 3-point or 4-point loading, with 3-point bending being the most common test.[8,9] It must be noted that the properties of the 3D printed retainers might change depending on several factors, including but not limited to the post-polymerization process[10], different printing technologies[11], and print angulation[12]. Proper retention of the result from the orthodontic treatment depends on the mechanical properties of the material from which the appliance is made.[13] Most studies on the topic of direct 3D printing of orthodontic retainers have been conducted in recent years, proving that the method is still in its early stage of development.[14]

AIM

The aim of this study was to carry out a comparative investigation of the mechanical properties (flexural strength and Young's modulus) of materials used for orthodontic retainers fabricated using direct 3D printing and thermoforming.

MATERIALS AND METHODS

For the purposes of this study, three groups of specimens from 3 different materials were manufactured according to ISO standard 20795-2:2013. Each group consisted of 7 specimens.

The first group of specimens was 3D printed using the Formlabs 3D printing system (Formlabs Inc., Somerville, Massachusetts, USA) and the Dental LT Clear V2 material (Formlabs Inc., Somerville, Massachusetts, USA) **(Fig. 1)**. An STL file of a specimen with the dimensions specified in the ISO standard was created using 3DSprint software (Vertex-Dental B.V., Soesterberg, The Netherlands). In the PreForm software (Formlabs Inc., Somerville, Massachusetts, USA), the support structures were generated, and the print job was sent to the Form 2 printer (Formlabs Inc., Somerville, Massachusetts, USA). After printing is done, the print platform is taken out from the printer and placed in the Form Wash Machine (Formlabs Inc., Somerville, Massachusetts, USA) which is filled with isopropyl alcohol to remove the excess non-polymerized material. The machine is set to 15 minutes. The specimens then get soaked in clean isopropyl alcohol for 5 minutes and are then left to air dry for 30 minutes, according to manufacturers' instructions. The post-polymerization process is carried out using the Form Cure machine (Formlabs Inc., Somerville, Massachusetts, USA) for 60 minutes at 60°C, according to manufacturers' instructions. The post-polymerization process allows

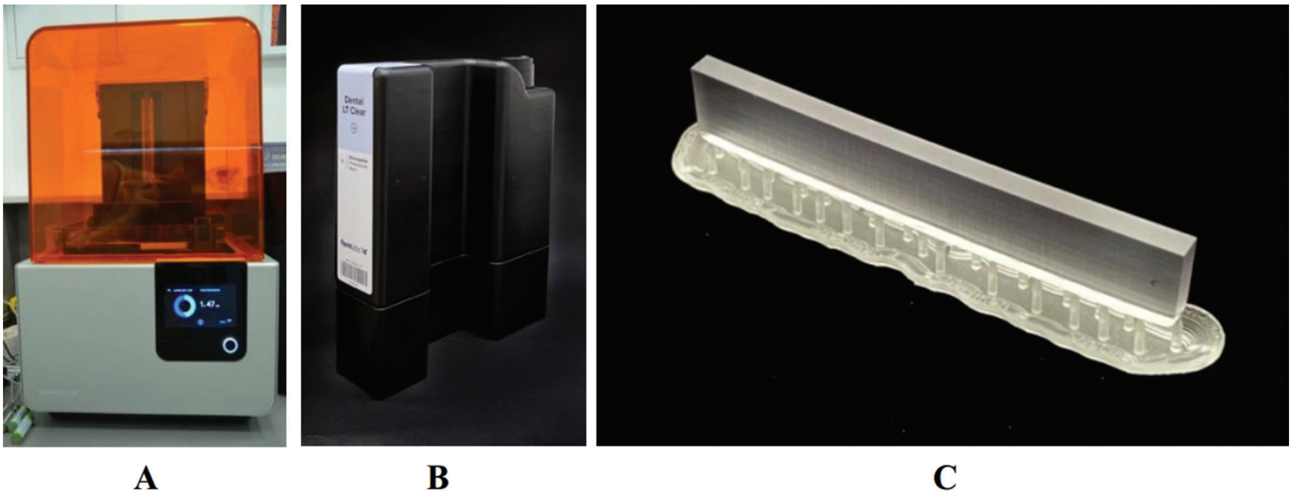

Figure 1. A. Formlabs Form 2 printer (Formlabs Inc., Somerville, Massachusetts, USA); **B**. Dental LT Clear V2 resin cartridge (Formlabs Inc., Somerville, Massachusetts, USA); **C**. 3D printed specimen.

the material to reach its optimal mechanical properties.[10] Afterwards, support structures were removed.

Specimens from the second group were 3D printed using the NextDent 3D printing system (Vertex-Dental B.V., Soesterberg, The Netherlands) and the NextDent OrthoFlex material (Vertex-Dental B.V., Soesterberg, The Netherlands) **(Fig. 2)**. The same STL file was imported in the '3D Sprint' software (Vertex-Dental B.V., Soesterberg, The Netherlands) and positioned on the virtual print platform. Supports were created and the print job was sent to the Next Dent 5100 3D printer (Vertex-Dental B.V., Soesterberg, The Netherlands). The resin was priorly mixed using the LC-3D mixer (Vertex-Dental B.V., Soesterberg, The Netherlands) for 5 minutes according to the manufacturer's instructions. Once the printing process finishes, the specimens are placed in 2 consecutive ultrasonic baths with 95% ethanol for a total of no more than 5 minutes. After removal of the excess non-polymerized resin with the ultrasonic baths, the specimens get air-dried for 10 minutes and are then placed in the LC-3Dprint Box light polymerization unit (Vertex-Dental B.V., Soesterberg, The Netherlands), which is equipped with 12 pcs of 18 W UV lights. The post-curing process takes 30 minutes, in which time the temperature inside can reach up to 80°C. Once the polymerization has finished, the specimens are left to cool down to room temperature and support structures are then removed.

The third group consisted of specimens made from Erkodur foils (ERKODENT, Germany) **(Fig. 3)**. In order to achieve the dimensions specified in the ISO standard, the specimens were cut using a circular saw.

The evaluation of the mechanical properties was carried out with the MultiTest 2.5-i machine (Mecmesin Limited) **(Fig. 4)**. The EMPEROR™ FORCE software was used to control the machine and to obtain the results. The selected test was that for flexural strength as it is most informative

Figure 2. **A**. Nextdent 5100 Printer (Vertex-Dental B.V., Soesterberg, The Netherlands); **B**. Orthoflex material (Vertex-Dental B.V., Soesterberg, The Netherlands); **C**. 3D printed specimen.

Figure 3. **A**. Specimen made out of Erkodur foil (ERKODENT, Germany); **B**. A pack of Erkodur foils (ERKODENT, Germany).

Figure 4. MultiTest 2.5-i machine (Mecmesin Limited).

regarding both how the material reacts to compression and tension. During the test, the upper side of the specimen is subjected to compressive strain and the lower side – to tension strain **(Fig. 5)**. F(max) refers to the force applied when failure in the material occurs. FS (Flexural strength) is a mathematical calculation derived from F(max), the dimensions of the specimen, and the distance between the supports. The software also calculates Young's modulus (E), which corresponds to the stiffness of the straight-line part of the stress-strain graph generated during the test. This region of the graph represents reversible elastic deformation because the stress remains below the proportional limit.[15] The statistical methods applied were descriptive statistics, Kruskal-Wallis test and Dunn's post-hoc test. The data was processed with STATA (StataCorp LLC, Texas, USA).

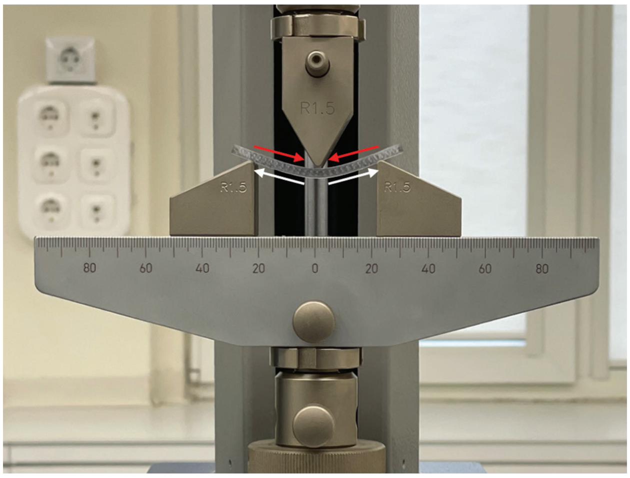

Figure 5. Testing flexural strength: compressive strain (red arrows) and tensile strain (white arrows).

RESULTS

The results were statistically analyzed and are presented in tables and charts below **(Tables 1-3, Figs 6-8)**.

The results for Fmax show the highest score for group 1 at 128.8 N±1.01 N and the lowest for group 2 at 99.27 N±5.01 N. Group 3 exhibited a mean maximum force of 115.42 N±0.37 N. According to a Kruskal-Wallis test (degrees of freedom=2, $\chi^2=17.818$, $p=0.0001$), there is a significant difference between materials with respect to Fmax. However, the Kruskal-Wallis test does not specify which pairs of groups are different. To assess that, we use Dunn's post-hoc test which shows that all groups differ when we compare them pairwise (all $p\leq0.0173$). **(Table 1, Fig. 6)**.

Table 1. Results for the maximum force (Fmax) achieved during the 3-point bend test, measured in Newtons (N)

Specimen group	Parameter		
	n	**$\bar{x}$ ± SD**	**Dunn's post-hoc test**
Group 1	7	128.8±1.01	$p_{1,2}=0.0000$
Group 2	7	99.27±5.01	$p_{1,3}=0.0173$
Group 3	7	115.42±0.37	$p_{2,3}=0.0173$

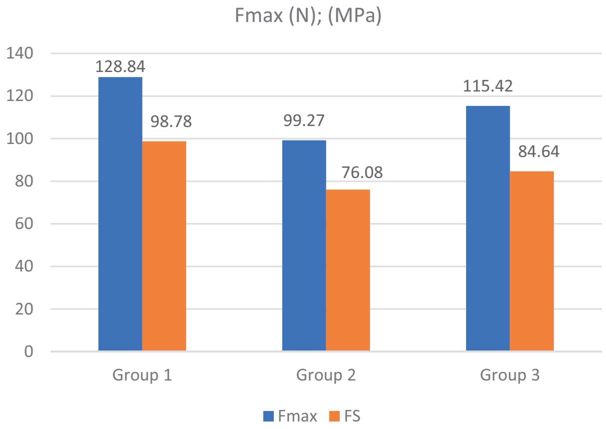

Figure 6. Graphical representation of the results for Fmax and FS.

As far as FS is concerned, the highest flexural strength was observed with group 1 (98.78 MPa±0.77 MPa), and the lowest - with group 2 (76.08 MPa±3.85 MPa). Group 3 showed a mean value of 84.64 MPa±0.27 MPa. According to a Kruskal-Wallis test (degrees of freedom=2, chi-squared=17.818, p=0.0001), there is a significant difference between materials with respect to FS. Dunn's post-hoc test shows that all groups differ when we compare them pairwise (all $p\leq0.0173$) **(Table 2, Fig. 6)**.

Table 2. Results for the flexural strength (FS) achieved during the 3-point bend test, measured in megapascals (MPa)

Specimen group	Parameter		
	n	x̄ ±SD	Dunn's post-hoc test
Group 1	7	98.78±0.77	$p_{1,2}$=0.0000
Group 2	7	76.08±3.85	$p_{1,3}$=0.0173
Group 3	7	84.64±0.27	$p_{2,3}$=0.0173

Table 3. Results for Young's modulus (E), measured in megapascals (MPa). Lower values show a more elastic material

Specimen group	Parameter		
	n	x̄ ±SD	Dunn's post-hoc-test
Group 1	7	2762.4±115.16	$p_{1,2}$=0.0258
Group 2	7	2393.05±158.13	$p_{1,3}$=0.0000
Group 3	7	1939.4±74.18	$p_{2,3}$=0.0137

The test of Young's modulus showed the following results: Group 1 exhibited the highest mean value at 2762.4 MPa±115.16 MPa, whereas group 3 scored the lowest at 1939.4 MPa±74.18 MPa. Group 2's mean Young's modulus was 2393.05 MPa±158.13 MPa. Kruskal-Wallis test shows that materials are different (Kruskal-Wallis test, df=2, χ^2=17.121, p=0.0002). Using Dunn's post-hoc test, comparing materials pairwise with respect to Young's modulus, we find that group 1 differs from group 3 (p=0.0000), group 2 differs from group 3 (p=0.0137), however, we did not find a significant difference between group 1 and group 2 (p=0.0258) (**Table 3**, **Fig. 7**).

During the tests, all specimens from group 1 were fractured under the forces of the testing machine. In group 2, the specimens bent with only a limited number showing cracks visible to the naked eye, but no complete fractures. All specimens from group 3 bent with no visible signs of fractures or cracks. Materials from group 1 showed the highest mean Young's modulus and group 3 – the lowest. As far as Fmax and FS are concerned, Group 1 shows the highest mean values and Group 2 – the lowest. Detailed results are shown in **Tables 1-3**. The mean values of all groups and parameters are represented graphically in **Figs 6, 7**.

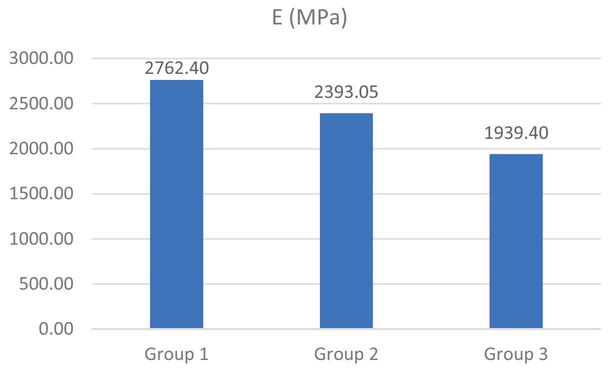

Figure 7. Graphical representation of the results for Young's modulus.

DISCUSSION

The results show that materials for direct 3D printing of orthodontic retainers are significantly less elastic when compared to thermoforming foils. This means that it is harder for directly 3D-printed retainers to overcome undercut areas when placing the appliance in the mouth and blocking out such areas to a certain degree during the CAD process might be a good idea. Higher rigidity is a desirable property for retainers as more rigid appliances have improved retention[13] and are better at counteracting the forces that might lead to orthodontic relapse. On the other hand, a higher Young's modulus presents a greater risk for material fractures during exploitation. Results from the current study show that differences observed amongst various materials used for 3D printing with the same clinical indications are not statistically significant. Nevertheless, we shall note that the p-value is very close to being statistically significant (p=0.0258; p<0.025 would show statistical significance).

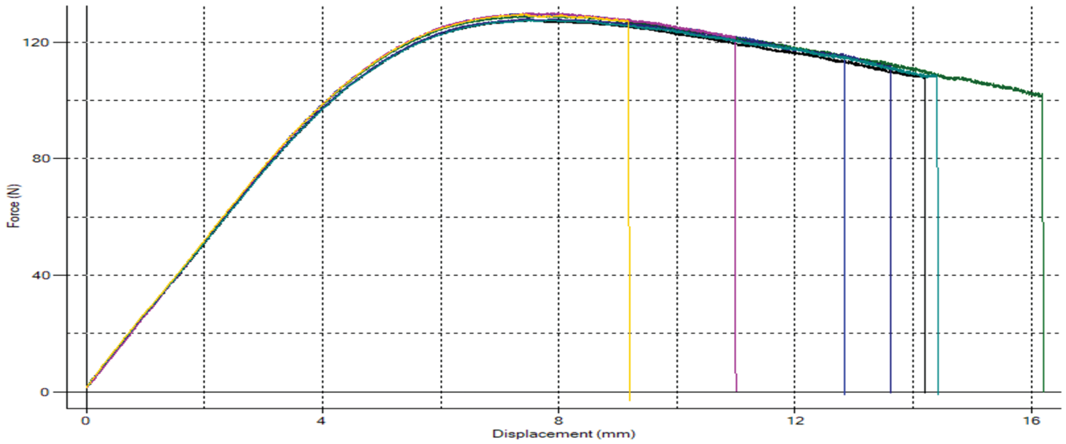

Figure 8. Stress-strain graph for specimens from group 1.

A study with a larger sample size might show slightly different p-values and might show statistically significant differences between materials from groups 1 and 2. The values the manufacturers state are lower than those found during the study, but are stated with a greater-than-or-equal-to sign (≥), indicating that higher values may be achieved. A possible explanation could be that depending on the time elapsed between initial polymerization (printing) and testing of the mechanical properties, the latter can change due to ongoing changes in the polymer chains. Another plausible cause of the established differences might be variations in the ambient temperature of the room in which the test was conducted.

It should also be noted that the properties of the retainer may be affected by several factors, among which are different printing technologies[11], print angulation[12], and thickness. Studies[16,17] show that the majority of orthodontists prefer a retainer thickness of 1 mm (if not greater). This also happens to be the minimum thickness for the 3D-printed retainers, as specified by the manufacturer. As stated in other studies, we confirm the opinion that 3D printing of orthodontic retainers is still in its early stage.[14]

CONCLUSIONS

The mechanical properties of materials for 3D printing of orthodontic retainers show statistically significant differences when compared to thermoforming foils, thus requiring extensive in vivo studies before being implemented in the daily clinical practice.

Limitations of the study

The results from this study only show the laboratory-tested properties of the materials. The oral environment in which the retainers function exhibits them to different conditions that might change the material's properties. To evaluate the effectiveness, comfort, and other qualities of 3D-printed retainers, extensive in vivo studies are needed before implementing them in the daily clinical practice.

Acknowledgements

The authors have no support to report.

Funding

This research was funded by the Medical University of Sofia under Grant 144/14.06.2022.

Competing Interests

The authors have declared that no competing interests exist.

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Механические свойства материалов для ортодонтических ретейнеров, напечатанных на 3D-принтере

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Дата получения: 31 мая 2023 ♦ **Дата приемки:** 24 августа 2023 ♦ **Дата публикации:** 31 декабря 2023

Образец цитирования: Stoev YY, Uzunov TT, Stoyanova NS, Grozdanova-Uzunova RG, Kosturkov DN, Taneva IK. Mechanical properties of materials for 3D printed orthodontic retainers. Folia Med (Plovdiv) 2023;65(6):986-992. doi: 10.3897/folmed.65.e107299.

Резюме

Цель: Целью данного исследования было сравнение механических свойств материалов, используемых для ортодонтических фиксаторов, изготовленных методами прямой 3D-печати и термоформования.

Материалы и методы: Двадцать один образец (*n*=7) из 3 различных материалов (Formlabs Dental LT Clear V2 – Formlabs Inc., Somerville, Массачусетс, США; NextDent Ortho Flex – Vertex-Dental B.V., Soesterberg, Нидерланды и Erkodent Erkodur – ERKODENT, Германия) был изготовлен и оценены их механические свойства. Две группы образцов были напечатаны на 3D-принтере, а другая изготовлена из материала для термоформования. Статистическими методами, которые мы применили, были описательная статистика, апостериорные тесты Kruskal-Wallis и Dunn.

Результаты: Что касается модуля Young (E), тест Kruskal-Wallis (df=2, χ^2=17.121, *p*=0.0002) показал значительную разницу между материалами для прямой 3D-печати ортодонтических фиксаторов (E=2762.4 MPa±115.16 MPa для 1-й группы и 2393.05 MPa±158.13 MPa для 2-й группы) и термоформовочной фольгой (E=1939.4 MPa±74.18 MPa). Статистически значимые различия были также обнаружены между прочностью на изгиб (FS) (критерий Краскела-Уоллиса, df=2, χ^2=17.818, *p*=0.0001) и F(max) (критерий Краскела-Уоллиса, df=2, χ^2=17.818, *p*=0.0001).

Заключение: Материалы, протестированные в настоящем исследовании, показали статистически значимые различия в модуле Young, прочности на изгиб и F(max).

Ключевые слова

ретенция, смола, ортодонтия, термоформование