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Research Article

Assessment of the Mechanical Properties of Three Commercially Available Thermoplastic Aligner Materials used for Orthodontic Treatment

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Abstract

Objectives: This studied aimed to measure the yield strength and stress relaxation properties of three commercially available thermoplastic aligner materials.
Methods: The three different thermoplastics aligner materials Duran (Scheu, Iserlohn, Germany), Erkodur (Pfalzgrafenweiler, Erkodent, Germany) and Track (Forestadent, Germany) were selected. A three-point bending test was carried out via the universal testing machine to measure their yield strength and stress relaxation properties. An independent *t*-test was performed for intergroup comparison. P-value < 0.05 was set as the level of significance.
Results: All the selected three polymers liberate a notable amount of stress during 24 hours. The highest stress release was observed in Duran i.e. 18.96 N/cm^2 as compared to Erkodur, which was 13.96 N/cm^2 and Track, which was 13.18 N/cm^2. The yield strength of Duran was the highest (75.85 Mpa) compared to Track and Erkodur with the yield strength of 52.75 Mpa and 55.86 Mpa, respectively.
Conclusions: Tooth movement is influenced by the composition of aligner material and its thickness. Duran had the highest stress release and yield strength. Stress released by different aligners exceeds around half of the initial stress value, which directly affects the orthodontic force application and subsequent tooth movement.

Keywords: Yield Strength, Stress Relaxation, Aligners, Mechanical Properties

1. Background

In the past decades, an alternative to the conventional fixed orthodontic appliances, especially among adult patients has gained more interest due to the improved aesthetic properties of new orthodontic appliances. In orthodontics, there are various aesthetical brackets and wires which have been developed for their use in clinical practice. More recently, a shift towards transparent thermoplastic removable appliances, named aligners, has been observed. Many companies provide these clear and aesthetic removable appliances, such as Invisalign, Clearsmile, and Clearalign, etc. for orthodontic patients. These aligners are made through computer aided design/computer aided manufacturing (CAD/CAM) technology or a stepwise setup model. They are used sequentially by patients for a given period (1). The concept of small tooth movements via thermoplastic appliances was presented in orthodontics by Kesling (1945) (2).

The aligners are made up of thermoplastic materials and possess different properties from the metal or ceramic components used in fixed orthodontics (3). Clear aligners are viscoelastic, i.e. having properties in between both elastic and viscous materials (4). Clinically, when an arch wire is inserted into the brackets, it applies force and moves the target tooth to its new position. Over time, the tooth starts moving and the arch wire comes to its original shape, while the forces keep on decreasing until they fall below the 'threshold' limit. The arch wire delivers orthodontic forces in proportion to its deformation and within its elastic limits, except for certain nickel-titanium (NiTi) wires. As a result, we can expect tooth movement and control it reasonably well using arch wires. In comparison, viscoelastic properties cause thermoplastic materials to deform under stress and there is a deformation of their mechanical properties with time. Such phenomenon is known as stress relaxation, which leads to decreased ability of the thermoplastic appliance to move a tooth with time, which altogether complicates the prediction of the orthodontic forces and the subsequent tooth movements. The complete duration of stress relaxation of the thermoplastic materials in the oral environment is always critical (5).

The amount or the magnitude of force has always been a significant focus in orthodontics. Having a thorough knowledge about the amount of force and the surface area of the PDL always helps to apply forces within the physiological limits. When the force is exerted on the crown, it is dispersed over all of the supporting structure. At the cellular level, distribution of stress (force per unit area), bone deformation (strain) and distortion of the periodontal ligament (shear stress, strain), are important to be considered. In addition, the remodeling response is directly proportional to the stress and strain levels within the periodontium (6).

At present, few researches on aligner materials have studied the stress released by orthodontic aligners, mainly because the ability of an aligner to move teeth depends on its material and the exact fitness. The companies providing aligners have never mentioned their exact mechanical properties.

2. Objectives

Hence to fill this lacuna, this research was performed in order to assess the stress release and yield strength (mechanical properties) of thermoplastic aligner materials.

3. Methods

In this in-vitro study, three different commercially available thermoplastic aligner materials obtainable from the market were selected and sheets with a thickness of 0.7 mm were used (Table 1). To avoid any errors in the readings, 10 sheets from each company were taken and tested upon. They were divided into three groups. Group 1, Duran, Scheu, Iserlohn, Germany; group 2, Erkodur Pfalzgrafenweiler, Erkodent, Germany; and group 3, Track, Forestadent, Germany.

The composition of each material was different, so their mechanical properties, such as yield strength and stress relaxation were also expected to differ from each other to some extent. Keeping the same loading geometry procedure and factors of the three-point bending test, a stress relaxation test was done three times on all sets of samples. The deflection was defined as the point in which the material passed a quarter of its yield strength. This value differentiated the viscoelastic properties of the materials from their elastic properties. This was done to attain viscoelastic characterization data valid for the material.

Table 1. Samples Tested in the Study

Brand Name	Firm	Material	Thickness, mm
Duran-group 1	Scheu, Iserlohn, Germany	PET-G	0.75
Erkodur-group 2	Pfalzgrafenweiler, Erkodent, Germany	PET-G/TPU	0.8
Track-group 3	Forestadent, Germany	PET-G	0.8

Abbreviations: PET-G, polyethylene terephthalate glycol; PET-G/TPU, thermoplastic polyurethane/polyurethane.

Rectangular cut samples (25 $\times$ 50 mm) of each material with 125 mm disks were trimmed and selected. A three-point bending test was then performed on all three materials on a universal testing machine (Star testing system, India model no. STS 248), equipped with a 100 N load cell. Testing protocols were followed as described by Lombardo et al7. Each sample was positioned on a stainless-steel stand, after bathing in distilled water at 37°C for 2 hours. A rectangular base having two equidistant vertical supports, 25 mm apart (the span) and 1 mm curvature radius, and was positioned under the load cell. Preloading was done and was set at 1 N (Figure 1).

Load-deflection test was done on each of the samples, with the specimen being deformed at a speed of 100 mm/min to a maximum deflection of 7 mm. The results were documented by the inbuilt software within the testing machine. For each sample, the load-deflection curve was created on the Microsoft excel sheet (Microsoft Corporation, Redmond wash). The following formula was used to assess, respectively, the yield load, yield strength, deformation, stiffness, and yield deflection of all samples (7): = $6h\delta/l^2$

Where = Strain (dimensional), s = sample width (mm), h = sample thickness (mm), l = span (mm), F = load (n), δ = deflection (mm), and σ = stress (mpa).

The subsequent stress relaxation tests were carried out at one-fourth of the yield strength as calculated before.

The same method and protocol were followed to assess the yield strength. Before the actual sample deflection test was performed, an initial pre-established force of 1 N was applied, and then the deflection recognized by the yield strength test was applied to each sample. This deflection was established within 5 seconds and was kept constant for the next 24 hours. In addition, the relaxation of the load was monitored until the end of the test. On all the 3 materials selected, three tests were performed for comparison of the curves to accurately evaluate the behavior of the

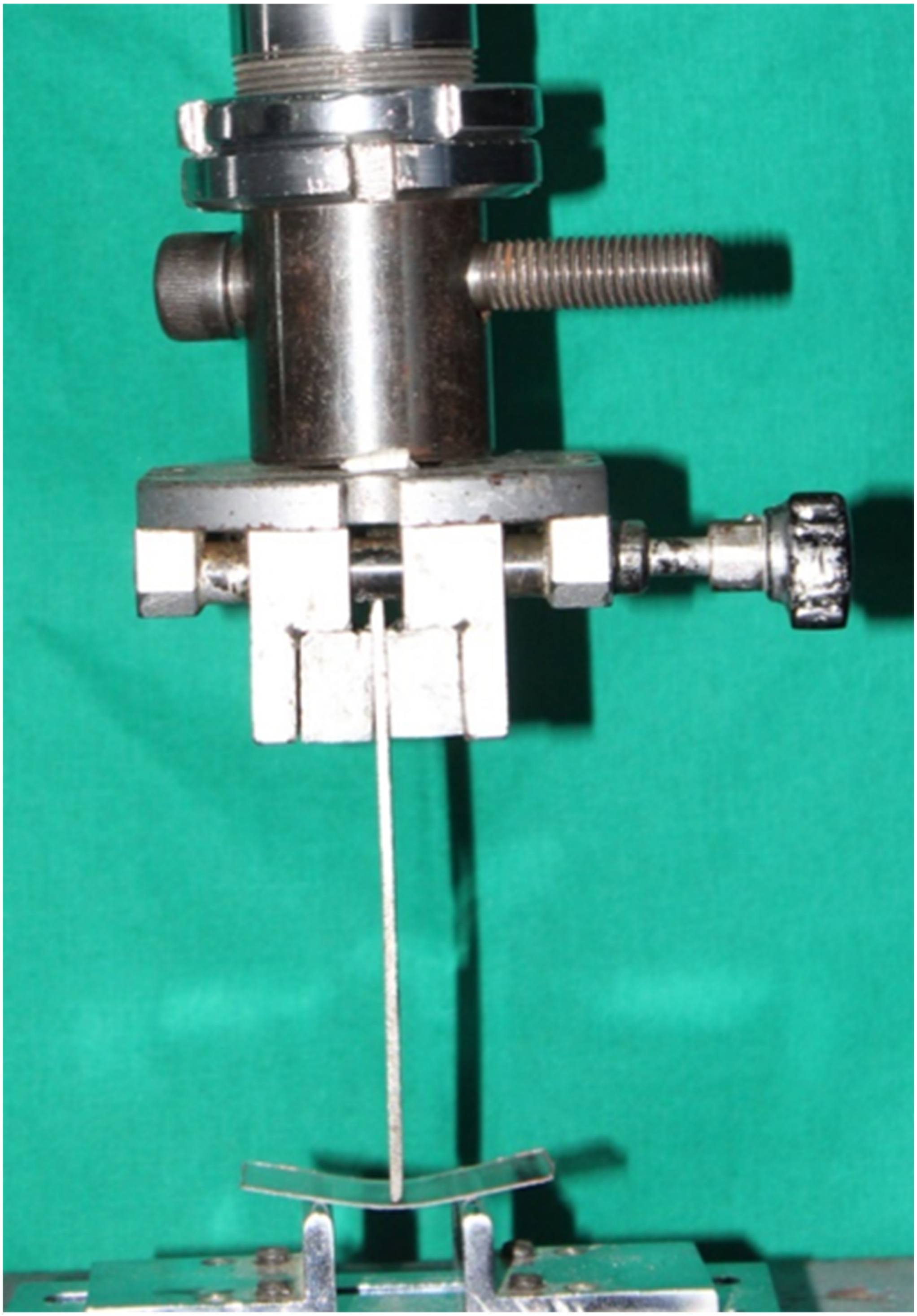

Figure 1. Universal testing machine

materials which can be put forward for a valid statistical analysis. A fresh sample was used for each test. A formula was used for comparison of the stress decay measured for each material during 24 hours. The normalized stress can be calculated as the percentage of stress decay (normalized stress %) (8) which was inferred as follows:

Normalized stress% = $\sigma_0/\sigma_{max} \times 100$

Where σ_{max} = maximum stress reached by each material during the stress relaxation test, and σ_0 = the initial stress value measured during the test. This formed equation was used to calculate the stress decay percentage after 24 hours for each material.

A master file was made, compiling all the collected data. It was then statistically analyzed via the Statistical Package for Social Sciences software (version 17) (SPSS Inc. Released 2008. Chicago: SPSS Inc). The data were descriptively analyzed for mean, standard deviation, and 95% confidence interval. P-value < 0.05 was considered significant. An independent *t*-test was performed for intergroup comparison.

4. Results

Figure 2 shows that Duran has more yield load and yield strength as compared to Erkodur and Track, while there was no statistically significant difference in deflection at one-fourth yield between Erkodur and track (Figure 3). Duran has a greater total initial stress, in addition to the highest decay during the first 24-hour interval. The Erkodur had the lowest initial and the final stress value. There was no significant difference in stress decay between track and Erkodur (P-value > 0.05). Duran had a higher percentage of stress relaxation, followed by track and Erkodur (Figures 4, 5).

5. Discussion

Thermoplastic materials have excellent aesthetical characteristics in addition to being simple to use for the patients. They have exceptional formability and are used as orthodontic retainers, for minor tooth movement, as temporomandibular joint splints, as periodontal splints, as mouth guards and for the fabrication of the bleaching trays. All these properties are ascribed to their great formability, higher shape-memory properties, and brilliant aesthetical characteristics (9). The development of CAD/CAM techniques over the past two decades has made it quite easy to fabricate these thermoplastic materials to be exactly designed and fabricated into a series of clear, removable tooth aligners for orthodontic tooth movements. The option of aligners has become more and more popular and in-demand than traditional fixed appliance systems as it bids several advantages including less pain, their transparency, requiring fewer office visits and the fact that they can easily be taken out for eating and brushing. Regardless of being widely used and accepted by patients worldwide, the mechanical properties of these thermoplastic appliances still remain uncertain (10). In our study, we assessed the mechanical properties of the three most commonly used thermoplastic aligner materials for orthodontic treatment. The results confirmed that all three aligners' material available in the market perform differently depending on their composition. The reason behind the degradation of the polymer can also be the mechanical and chemical effects of the materials (11). Previously, many in-vitro and in-vivo tests were conducted to study the stiffness of the materials by performing three-point bending and the nanoindentation tests, emphasizing the significance of exerting an appropriate force to move the teeth in a desired and planned way, as well as minimizing the damage to their periodontal support (12). However, in our study, we have investigated and compared the stress relaxation properties of the materials used. Ideally, any orthodontic appliance should apply a light force that is persistent over time and the same is expected from the thermoplastic aligner sheets. Orthodontic treatment requires the delivery of an ideal and optimal force, which helps to maximize the rate of tooth movement with the least irreversible damage to the underlying periodontium. It has been reported that the optimal force required for the tipping movement of a single tooth is 50 g to 75 g (13). Treatment effectiveness with clear aligners has been reported to be 41% to 59%. For the aligner material to exert optimum orthodontic forces, the ideal material should possess a high yield strength to certify that the forces are applied within the elastic range. Considering that each aligner is designed to move a tooth or a group of teeth around 0.25 to 0.33 mm over 14 days, the relaxation curve should be flat and should fairly exert a continuous force overtime (14). Nevertheless, among these three aligner materials, Duran shows better yield strength and stress relaxation properties (15).

Kohda et al. (1) investigated these three aligner materials for their mechanical properties, thickness and the amount of activation for orthodontic forces and they concluded that the orthodontic forces delivered by the aligners depend on the material thickness and the amount of activation (1, 16). Our findings confirm that the stress decay was rapid during initial hours and higher in Duran compared to other thermoplastic materials used. Polyester, polyurethane and polypropylene are the dominant thermoplastic materials used in the fabrication of clear orthodontic appliances (17, 18). Out of which, polyethylene terephthalate (PET) is the most frequently used thermoplastic material because of its good creep properties, fatigue resistance, and its dimensional stability (19, 20). Zhang et al. (13) studied the mechanical properties of mod-

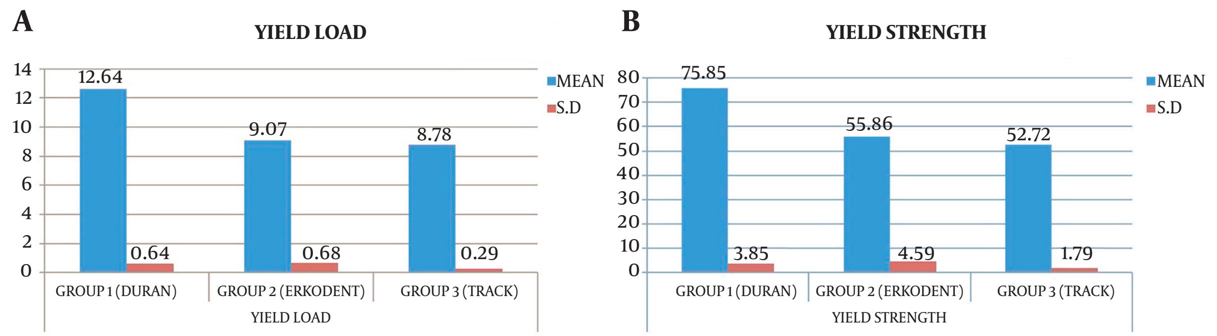

Figure 2. A, yield load chart: Group 1-Duran, group 2-Erkodur, and group 3-Track; B, yield strength: Group 1-Duran, group 2-Erkodur, and group 3-Track

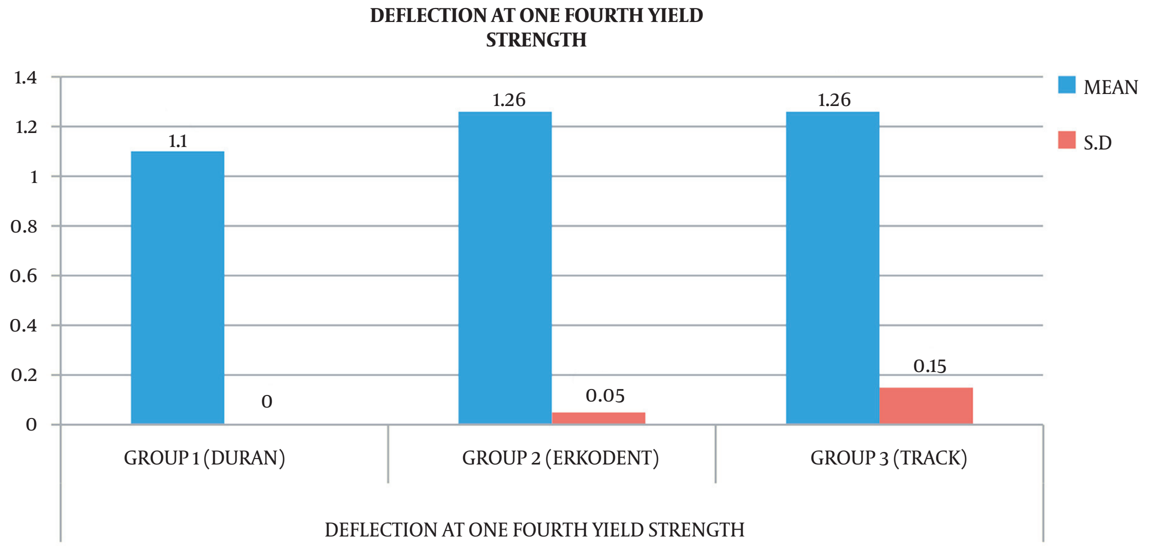

Figure 3. Deflection at one fourth yield strength: Group 1-Duran, group 2-Erkodur, and group 3-Track

ified PET/polycarbonates (PC)/thermoplastic polyurethane (TPU) blend using a universal testing machine. They compared the results with two commercial thermoplastic products, Erkodur and Biolon, and found that the tear strength was 50.23 MPa and the elongation at break was 155.99%. The stress relaxation rate was 0.0136 N/s after 1 hour, and it was considerably slower than Erkodur and Biolon ($P < 0.05$). Our findings confirm a substantial difference in the decrease of force level among all three groups of aligner materials. There was no statistically significant difference between Erkodur and Track. The yield strength for Duran was found significantly higher compared to the other two groups. This study was conducted in an in-vitro setting; hence the results may be different in the oral cavity where there are many external factors which cannot be accounted for in this study, including saliva, uneven occlusal forces, cleaning solutions, wear time and oral hygiene. Leeching of the aligner material may also take place due to varying pH levels in the oral cavity. All these factors should be considered. This study sheds some light on the mechanical properties of the aligner materials in the lab. The results can be used to improve the materials to be more durable so that they will not deform or break in the oral cavity. Further clinical studies are needed to understand the mechanical properties of these materials in the oral environment.

This study has the following limitations:

1) The study evaluates the behavior of different aligner materials, which are not equal in compositions.

2) The heat treatment performed to form the aligners

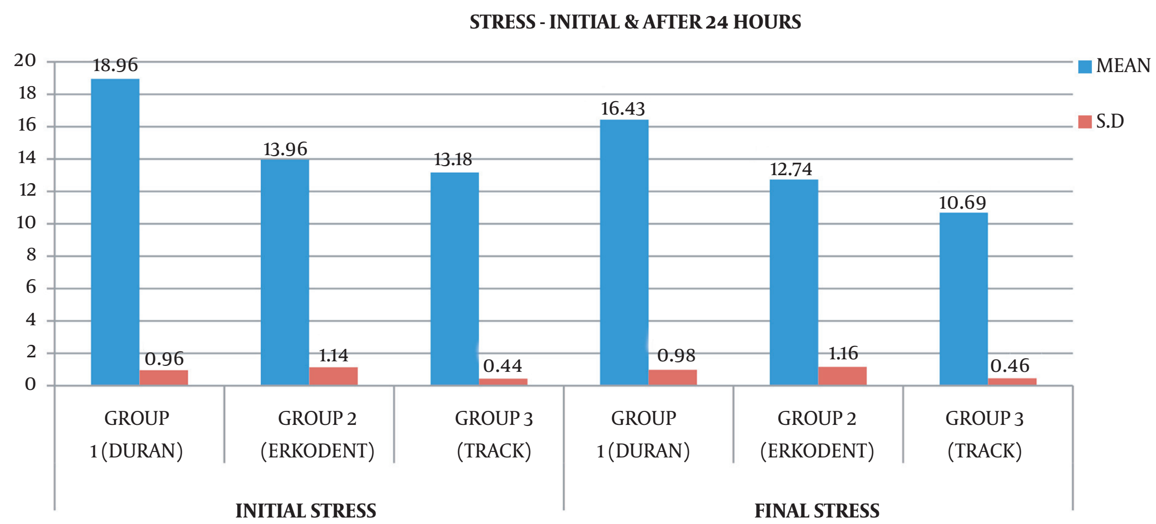

Figure 4. Comparison of initial and final stress after 24 hours

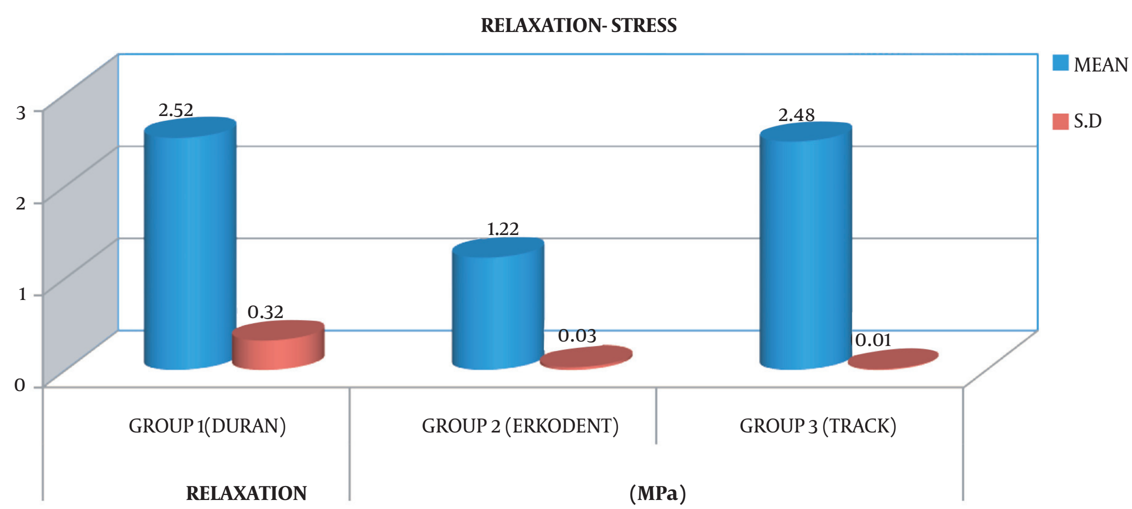

Figure 5. Comparison of stress relaxation between Duran, Erkodur, track

might cause a change in the behavior of chosen samples and these characteristics may not remain the same under the masticatory, physical and chemical stress occurring in the oral cavity

3) Further studies have to be carried out to better understand the effects of thermoforming and intraoral environment on these materials. Testing them after thermoforming and clinical use is recommended for future researches.

5.1. Conclusions

The commercially available thermoplastic materials may vary in their mechanical characteristics. Among all three types tested, both Erkodur and Track have lower stiffness compared to Duran. All three materials behaved similarly in the 24-hour stress decay test, with greater initial stress during the first 8 hours after loading which followed a gentle decrease and finally plateaued. A high velocity of stress relaxation in 24 hours was reported in Track. Regarding the decay rates, the Duran had the smallest decay rate compared to the other two materials. The initial stress value in Duran was less compared to Track, but marginally above Erkodur. To assess the real-life behavior of the aligners, further in-vivo studies should be performed in order to assess the clinical performance of orthodontic aligners during treatment.

Footnotes

Authors' Contribution: AR and AKB carried out the research work in gathering the articles for the study, thought of the concept and drafted the manuscript. AP, VV, and APa participated in the structuring the research, defined the intellectual content and performed the quality check. RK, AR, and AKB conceived of the study and participated in its design, coordination and helped to draft the final manuscript. RK, AP, VV, and AR were part of the manuscript preparation, editing and reviewing. All the authors read and approved the final manuscript.

Conflict of Interests: All authors state that there is no conflict of interest.

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