

Original Article

Comparison of Force Delivery Profiles Between Thermoformed Aligners and Direct Printed Aligners During Canine Rotation: An *In Vitro* Study

Mahalakshmi Krishnakumaran, Roshini T., Parameswaran T.M., Balaji Krishnan, Deepak Prabhu

Tagore Dental College and Hospital, Rathinamangalam, Chennai 600127, India

Received: 22 June 2026

Accepted: 13 July 2026

Published online: 30 July 2026

Keywords: clear aligners, thermoformed aligners, 3D printed aligners, force delivery, aging, orthodontic

Clear aligner therapy has become increasingly popular owing to its aesthetic and functional benefits; however, the force delivery characteristics of various aligner materials are not well understood. The advent of direct 3D-printed aligners has necessitated their comparison with traditional thermoformed materials. This study aimed to evaluate the force delivery of thermoformed (Zendura Viva) and direct 3D-printed (TA28) clear aligners during 1° and 2° rotational tooth movements, both before and after artificial aging. A total of 24 aligners were produced and categorized into two primary groups based on the material: thermoformed (Zendura Viva) and direct 3D-printed (TA28). Each group was further divided into subgroups for 1° and 2° rotational activation (n= 6 per subgroup). Force measurements were obtained using an FSR402 sensor integrated with an Arduino-based system under standardized conditions before (T0) and after artificial aging (T1), which involved thermocycling and incubation in artificial saliva. The initial force values of the thermoformed aligners were significantly higher than those of the direct 3D-printed aligners ($p < 0.001$). Artificial aging led to a notable reduction in force for both materials across all groups ($P < 0.001$). The three-way ANOVA revealed significant effects of material and aging, as well as a significant interaction between material and aging ($p < 0.001$), whereas the degree of rotation did not have a significant independent effect ($p > 0.05$). After aging, no statistically significant differences were observed between the materials. Thermoformed aligners provide higher initial forces; however, both thermoformed and direct 3D-printed aligners experience significant force degradation after aging, resulting in similar residual force levels. The degree of rotational activation has a limited impact on the long-term force delivery. These findings underscore the importance of material selection and force sustainability in optimizing orthodontic treatment using clear aligners.

Introduction

The rising demand for aesthetic solutions has contributed to the widespread acceptance of clear aligner therapy, as individuals increasingly seek alternatives to traditional orthodontic appliances. Over the past decade, clear aligners have gained popularity due to their aesthetic appeal and comfort [1]. In 1999, Align Technology launched the first commercial clear aligner system, known as Invisalign [2]. A significant development in this field was the introduction of the first aligner resin suitable for direct printing. The aligner resin, TC-85DAC (Graphy, Seoul, Korea), was introduced in 2019 and has become prominent in aligner production [3]. The TA-28 resin was subsequently introduced for direct 3D-printed clear aligners to address the clinical and manufacturing

limitations identified in earlier materials, such as TC-85.

It is not feasible to directly apply the biomechanics of traditional fixed appliances to aligner therapy, nor is the force system generated by aligners well understood. Unlike fixed appliances, which have distinct force application points at the brackets and archwire, clear aligners encompass the entire tooth crown, complicating the identification of precise force application points [4]. Compared with fixed braces, the force system of aligners is more complex, as there are no specific known points for force application, and multiple parameters are used to determine the treatment outcome.

The biomechanical characteristics of aligners are influenced by factors such as aligner thickness, extension, material properties, amount of activation, and attachments used [5-7]. As the orthodontic force of

*Corresponding author: Dr. Mahalakshmi Krishnakumaran
E-mail address: mahakrishnasai@gmail.com

<https://doi.org/10.65795/vkxn9g80>

#20032726/©2026 The Author(s). Published by the Society for Biomaterials and Artificial Organs (India), Thiruvananthapuram, India. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the published article in a repository by the author(s) or with their consent.



transparent aligners and their intricate biomechanical characteristics are currently assessed solely through clinical experience, the predictive value of the outcomes of invisible orthodontic treatment is limited. Precise measurement of the force exerted by clear aligners is essential for developing effective orthodontic treatment regimens.

Two primary orthodontic simulation force measurement techniques have recently been developed for clear aligners: finite element analysis and experimental methods. However, directly assessing orthodontic forces within the intraoral environment remains unfeasible due to the complex biomechanics involved [8]. The predictability of clear aligner therapy for certain dental movements, particularly rotations, is comparatively limited when contrasted with fixed appliances [9,10]. This study investigates the comparative force delivery of thermoformed and direct 3D-printed clear aligners during 1° and 2° rotational tooth corrections, emphasizing the influence of aligner material type and activation degree on orthodontic force magnitude before and after artificial aging. The methodology incorporates the FSR402 Sensor to provide precise force measurements.

Materials and Methods

The study was approved by the institute's ethical committee [TDCH IEC NO: 03062502]. Based on a previous study by Zamani et al. [11], the sample size was calculated as six per group for this pilot study.

A priori power analysis was conducted using G*Power (version 3.1) to determine the required sample size for a one-way fixed-effects omnibus ANOVA across four independent groups. Assuming a large effect size ($f = 1.0410998$), a significance level (α) of 0.05, and a desired statistical power ($1 - \beta$) of 0.95, the analysis yielded a noncentrality parameter (λ) of 26.0133310. To achieve these parameters, a total sample size of 24 participants (or 6 participants per group) is required, yielding a critical $F(3, 20) = 3.0983912$ and an actual statistical power of 0.9599553.

Participants were selected based on Angle Class I molar relationships and minor mesial rotation of the maxillary right canine. Individuals with dental crowding greater than 5 mm, periodontal complications, or transverse discrepancies were excluded. Eligible participants underwent intraoral scanning using an Aoralscan 3 Intraoral Scanner (Shining 3D, China), and the scans were saved as STL files.

In Group 1 ($n=12$), the STL files were processed using the Direct Aligner Designer software to organize, clean, and add a virtual base to each scan. Group 1a ($n=6$) had aligners with a 1-degree rotation per tray, whereas Group 1b ($n=6$) had a 2-degree rotation per tray. The aligner shells were created and exported as 3D shells, which were then transferred to slicing software (Uniz). The sliced files were sent to the 3D printer via USB or wireless connection. The aligners were printed using Tera Harz TA28 resin in a Uniz Nbee 3D printer (110 V/60 Hz-6 A, 220 V/50 Hz 3 A, XY resolution -49.8 μm) at a thickness of 0.7 mm. The uncured resin was removed by centrifugation for approximately 3–4 min at 500 rpm and 50V in a Tera Harz Spinner (THSP Graphy, Seoul, South Korea). Subsequently, the supports were removed, and post-production curing was conducted using Cure M (Graphy, Seoul, Republic of Korea) with a UV irradiance of 1,000 mw/cm^2 and a UV energy density of 280,000 mj/cm^2 , for 24 min. A nitrogen production curing unit was employed to create an inert environment to prevent the formation of oxygen-inhibition layers. The aligners were then immersed in boiling water (100°C) for 1 min and placed in an ultrasonic bath (24 W, 42 kHz) for 5 min.

In Group 2 ($n=12$), the STL files were imported into the Maestro 3D Dental Studio software (AGE Solutions Srl, Italy) for virtual treatment planning. Tooth rotations of 1° (Group 2a, $n=6$) and 2° (Group 2b, $n=6$) were applied per model to derotate 13. Following the creation of a virtual model, Chitu Box v1.9.5 Workshop slicing software (All-in-one SLA/DLP/LCD Slicer, Shenzhen CBD Technology, China) was used to slice the model at equal intervals, and the dental models were printed at a 100-micron resolution in the Z plane using a Phrozen Sonic Mini-S printer. The printed models were soaked in 99% isopropyl alcohol for 15 min, air-dried, and post-cured for 15 min in an Anycubic

Cure Machine (wavelength: 385-405 nm; Anycubic Technology Co., Shenzhen, China). The thermoforming process was completed using a Ministar S machine (Scheu Dental Ministar), and Zendura Viva sheets (thickness: 0.8 mm; Bay Material LLC, Fremont, CA, USA) were thermoformed. The aligners were allowed to cool and harden before being trimmed (trim line -2 mm above the gingival margin) and polished for a smooth fit.

To simulate 10 days of intraoral use, the clear aligners were immersed in artificial saliva within an incubator maintained at 37°C, thereby replicating body temperature (T1). Subsequently, thermocycling was performed to emulate the temperature variations characteristic of the oral cavity. This procedure involved 500 cycles between water baths set at 5 and 55°C, with a 30-s interval in each bath to simulate the thermal stress associated with the consumption of hot and cold foods and beverages.

Assessment of force

The FSR402 sensor (figure 1) (thin-film pressure sensor type pressure transducer force-sensitive resistor long tail 0–10 kg for 1.27cm/0.5 in diameter, Walfont) was incorporated into an electrical circuit using a voltage divider configuration with a 10 ohm pull-down resistor. The sensor was then connected to an Arduino Uno (UNO R3 Board ATmega328P, BSROBOTIC) to enable continuous analog data collection using a C++ program. Calibration was conducted using precision pharmacological weights classified as Class M1, which were applied in 0.1 N increments until a maximum value of 10 N. Polymer thick-film force-sensitive resistors (FSRs) inherently exhibit a non-linear inverse relationship between resistance and force across their entire operational range. However, for the specific experimental window of 0–10 N, a localized linear approximation was employed. Within this range, force estimation was determined using a corrected linear calibration formula: $F(\text{N}) = 0.009775 * (1023 - \text{ADC reading})$.

This linear regression model demonstrated exceptionally high predictive validity, with a coefficient of determination ($R^2 = 0.9999$). The linearized model was chosen to minimize processing demands on the microcontroller during real-time data collection while maintaining experimental accuracy within the defined study parameters. To address the cross-sensitivity of thin-film sensors to surface curvature and boundary edge-loading when applied to the canine crown, an in-situ calibration protocol was implemented. The FSR sensor was pre-curved to conform to the specific anatomical contours of the target tooth surface before initiating the weight-calibration sequence. The structural baseline strain and parasitic resistance offsets resulting from this mechanical bending were mathematically adjusted and nullified under zero-load conditions (figure 2).

Data acquisition commenced after a 3-s pause to allow stress levels to stabilize. Multiple readings were obtained and averaged for each sample to ensure the precision. The aligners designed for this study induced movements of 2° or 1° in 13 tooth region. Both thermoformed and direct-printed aligners were assessed under the same conditions before (T0) and after aging (T1). The direct printed aligners were placed in the



Figure 1: FSR402 sensor interfaced with an Arduino Uno

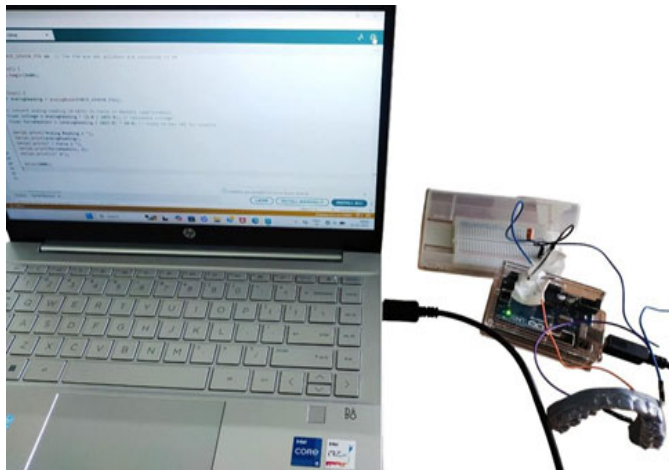


Figure 2: FSR placed between the aligner and target tooth

water bath at 37–40°C for 1 to 2 minutes before insertion to soften the material. The conversion from analog data to voltage is expressed as $V = (\text{ADC reading} \times 5 \text{ V}) / 1023$. The resistance was determined using the formula $R_{\text{FSR}} = 10 \text{ k ohm} \times (5/V - 1)$.

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics (version 20; IBM Corp., Armonk, NY, USA), with statistical significance set at $p < 0.05$. Descriptive statistics, including the mean and standard deviation, were calculated for all groups. The normality of the data distribution was assessed using the Shapiro–Wilk test, and the homogeneity of variances was evaluated using Levene’s test. In a longitudinal assessment of the same 24 aligner specimens across different time intervals, a three-way mixed-design ANOVA, also known as split-plot ANOVA, was conducted. The aligner material type (Zendura Viva vs. TA28) and the degree of activation (1° vs. 2° rotation) were considered as between-subject factors. Meanwhile, the artificial aging interval (before [T0] vs. after [T1]) was treated as a dependent, repeated-measures within-subject factor.

Type III sums of squares was conducted to determine the effects of aligner material (Zendura Viva vs. TA28), degree of rotation (1° vs. 2°), and aging (before vs. after), along with their interaction effects on force delivery. When statistically significant differences were observed, Tukey’s Honestly Significant Difference (HSD) post hoc test was applied for pairwise comparisons. The intraclass correlation coefficient (ICC) was

Table 1: Descriptive statistics showing mean and standard deviation ($M \pm SD$) for force measurements across all experimental conditions

	1 Degree Rotation (Mean $\pm$ SD)		2 Degree Rotation (Mean $\pm$ SD)	
	Before Aging	After Aging	Before Aging	After Aging
Zendura Viva	3.85 ± 0.22	0.41 ± 0.27	4.18 ± 0.29	0.35 ± 0.06
TA 28	0.80 ± 0.14	0.16 ± 0.07	1.08 ± 0.13	0.09 ± 0.01

calculated using a two-way mixed-effects model with a consistency definition to assess the reliability and reproducibility of the measurements performed.

Results

In table 1, the mean and standard deviation (SD) were calculated for each combination of material, rotation (1° and 2°), and time (before and after the aging process). Prior to aging, the thermoformed aligners (Zendura Viva) demonstrated significantly higher mean force values ($3.85 \pm 0.22 \text{ N}$ at 1° and $4.18 \pm 0.29 \text{ N}$ at 2°) than the direct 3D-printed aligners (TA 28), which exhibited considerably lower forces ($0.80 \pm 0.14 \text{ N}$ and $1.08 \pm 0.13 \text{ N}$, respectively). Following aging, both materials experienced a notable reduction in force, with Zendura Viva decreasing to $0.41 \pm 0.27 \text{ N}$ (1°) and $0.35 \pm 0.06 \text{ N}$ (2°), and TA 28 decreasing to $0.16 \pm 0.07 \text{ N}$ (1°) and $0.09 \pm 0.01 \text{ N}$ (2°). The relatively small SD values indicate consistent measurements within the groups, whereas the evident decline in the mean values highlights significant force degradation after aging.

The three-way mixed-design ANOVA (Split-Plot ANOVA) (table 2) was conducted to partition the experimental variance into independent between-subjects effects (aligner material and rotation degree) and longitudinal, within-subjects repeated measures (artificial aging). Regarding the between-subjects effects, the selection of aligner material (Zendura Viva vs. TA 28) had a substantial and statistically significant influence on global force delivery ($F = 354.25$, $p < 0.001$), indicating that the thermoformed material maintains significantly higher mechanical force levels than the direct-printed resin when averaged across all time points. In contrast, the baseline prescription of rotation degree ($F = 1.71$, $p = 0.205$) and its two-way interaction with material type ($\text{MAT} \times \text{ROT}$: $F = 0.03$, $p = 0.874$) were statistically non-significant, suggesting that increasing the initial structural activation from 1° to 2° did not alter the global baseline force profile as markedly as changing the core polymer substrate. For the within-subjects tier, the longitudinal variable of artificial aging exhibited a pronounced and highly significant main effect ($F = 3689.52$, $p < 0.001$), demonstrating that thermocycling fatigue and

Table 2: Three-way mixed-design Anova (Type III sum of squares) examining the effects of material type, rotation degree, and longitudinal artificial aging on force deliver

Source of variation	Type III sum of squares (SS)	Degrees of freedom (df)	Mean square (MS)	F-value	P-value	Significance
Between-Subjects Tier						
Aligner material (MAT)	16.401	1	16.401	354.25	< 0.001	S (***)
Rotation degree (ROT)	0.079	1	0.079	1.71	0.205	NS
MAT $\times$ ROT	0.001	1	0.001	0.03	0.874	NS
Error (between-subjects)	0.926	20	0.046			
Within-Subjects Tier (Repeated Measures)						
Artificial aging (time)	59.764	1	59.764	3689.52	< 0.001	S (***)
MAT $\times$ time	11.704	1	11.704	722.55	< 0.001	S (***)
ROT $\times$ time	0.205	1	0.205	12.68	0.002	S (**)
MAT $\times$ ROT $\times$ time	0.001	1	0.001	0.03	0.858	NS
Error (within-subjects)	0.324	20	0.016			
Total variance scale	118.476	47				

Table 3: Tukey honestly significant difference (HSD) post-hoc test for pairwise comparisons

Comparison category	Specific groups	Mean Difference (n)	P-value (adjusted)	Significance
Inter group comparison(cross sectional)				
Material comparison	TA (printed) vs. ZV (thermoformed)			
(Effect of Material)	Before aging (at 1° Rotation)	3.05	< 0.001	***
	Before aging (at 2° Rotation)	3.08	< 0.001	***
	After aging (at 1° Rotation)	0.25	0.354	NS
	After aging (at 2° Rotation)	0.26	0.307	NS
Intragroup comparisons				
Activation comparison	1 degree vs. 2 degree rotation			
(Effect of activation)	Zendura viva (before aging)	0.33	0.089	NS
	Direct printed (before aging)	0.30	0.158	NS
	Zendura viva (after aging)	-0.06	0.999	NS
	Direct printed (after aging)	-0.07	0.998	NS
Aging Impact	Before vs. After artificial aging			
(Effect of Time)	Zendura Viva (at 1° rotation)	3.44	< 0.001	***
	Zendura Viva (at 2° rotation)	3.83	< 0.001	***
	Direct printed (at 1° rotation)	0.64	< 0.001	***
	Direct printed (at 2° rotation)	1.01	< 0.001	***

NS - Not significant. * significant

moisture incubation in artificial saliva induce significant force decay across all experimental units. Notably, the highly significant material $\times$ aging interaction (MAT $\times$ TIME: $F=722.55$, $p<0.001$) constitutes the core biomechanical finding of this study: it quantitatively establishes that Zendura Viva undergoes a significantly steeper and more severe absolute force reduction over time compared to the more stable, lower-intensity degradation curve observed in the direct-printed TA 28 resin. Furthermore, a significant rotation $\times$ aging interaction (ROT $\times$ TIME: $F=12.68$, $p=0.002$) indicates that the rate of structural relaxation varies with the initial degree of rotational activation. Finally, the three-way interaction (MAT $\times$ ROT $\times$ TIME: $F=0.03$, $p=0.858$) was non-significant, suggesting that the combined variables did not exhibit chaotic degradation behaviors beyond their established independent and two-way interaction pathways.

A post hoc analysis (multiple comparisons with adjusted p-values) (table 3) was conducted to identify specific group differences following ANOVA. Before aging, Zendura Viva produced significantly higher forces than TA 28 at both 1° and 2° rotations ($p<0.001$). However, after aging, the difference between the materials was no longer statistically significant ($p>0.05$), indicating that both materials converged to similarly low force levels over time. When comparing activation levels (1° vs. 2°), no significant differences were observed within either material before or after aging, suggesting that increasing activation did not significantly alter force delivery. In contrast, comparisons between time points showed a highly significant reduction in force for both materials at both activation levels ($p<0.001$), confirming that aging is the most influential factor on the force reduction. Overall, the post hoc results reinforce that while material differences are evident initially, aging leads to a universal and significant decline in force, irrespective of the material or activation level.

Discussion

Orthodontic tooth movement is a biologically mediated process that occurs in response to the application of controlled mechanical forces, leading to the remodeling of the periodontal ligament and surrounding alveolar bone. The magnitude, direction, and duration of the applied force are critical determinants of the rate and quality of tooth movement in orthodontics. Light, continuous forces are generally considered optimal because they facilitate physiological bone remodeling while minimizing adverse effects such as hyalinization or root resorption⁵. In clear aligner therapy, the delivery of force differs significantly from that of conventional fixed appliances [12]. The selection of materials plays a pivotal role in determining the magnitude and distribution of the force

exerted on the tooth during orthodontic treatment. Different materials vary in their mechanical properties, such as elasticity, stiffness, and resilience, which directly affect the transmission of force through the aligner to the tooth surface. For instance, materials with higher stiffness may deliver more concentrated forces, whereas more flexible materials could distribute force more evenly, potentially influencing treatment efficiency and patient comfort [13,14]. Aging of orthodontic aligners in an experimental or *in vitro* setting is performed using standardized artificial aging protocols and simulates the oral environment and its effects on mechanical and optical properties. It causes hydrolytic aging and mechanical property reduction similar to what occurs over time in the oral cavity [15]. Furthermore, thermocycling protocols that mimic the temperature variations occurring in the oral cavity have been applied to accelerate the aging of aligners. For example, aligners subjected to thermocycling ranging from approximately 50 to 700 cycles, simulating day-to-day temperature fluctuations, showed measurable changes in tensile strength and surface condition over time points, including 7 days [16,17]. When aligner sheets are immersed in water, the absorption of water molecules into the plastic through diffusion between polymer chains, encouraged by elevated temperatures, increases polymer mobility and has a plasticizing effect, which eventually weakens the plastic. Thus, controlled laboratory aging protocols aims to reproduce these effects in shorter periods under accelerated conditions of aging.

In our study, we opted for the TA 28, a photopolymer with a cross-linked polymer structure direct printing aligner resin, owing to its established biocompatibility, which complies with EN ISO 10993-5 standards for non-cytotoxicity, even at print thicknesses reaching up to 6 mm, as long as standardized post-curing protocols are observed. This selection ensures patient safety and dependable intraoral applications. Additionally, TA-28 permits the customization of variable layer thicknesses within a single aligner, allowing for precise modulation of flexibility and force distribution across various dental regions, which may improve treatment effectiveness and patient comfort. From a mechanical perspective, TA-28 possesses the necessary compressive strength and durability for effective orthodontic force application, and its shape memory and viscoelastic characteristics contribute to maintaining a consistent force over time, despite repeated use. The ability to fabricate aligners with precise geometry, controlled thickness, and reduced auxiliary attachments through 3D printing further enhances manufacturing reliability and clinical predictability with TA-28 [6,18,19].

Zendura Viva is meticulously designed as a flexible, multi-layer thermoplastic polyurethane (TPU)-based material, specifically engineered to facilitate resilient force transmission in dental aligners. This design pri-

orizes both patient comfort and durability under repeated thermal and mechanical stresses [20]. Compared with other commonly utilized thermoplastic polymers and materials, such as Duran or Essix, Zendura typically exhibits slightly lower forces in mechanical bending tests prior to forming. This characteristic reflects a balance aimed at optimizing patient comfort and orthodontic effectiveness [21]. Additionally, the multilayer structure of Zendura Viva enhances its performance in maintaining force throughout the wear period, which is a critical factor for aligners that must apply consistent forces as the teeth gradually move.

Aligners are recognized for exerting an initial force upon insertion, which gradually diminishes over time due to the stress relaxation properties inherent in the thermoplastic materials employed [22], aligning with biomechanical recommendations for orthodontic forces in the range of 0.2–2.5 N and deliver light and continuous forces within the physiological range [23,24].

In our study, both thermoformed and direct-printed aligners exhibited this characteristic force profile, with a distinct initial force peak upon placement that progressively decreased. This observed pattern aligns with the findings of Simon et al. [25] who documented that the aligners generated an initial force that decreased exponentially over time. Similarly, Cremonini et al. [26] observed that direct-printed aligners generally exert lower forces compared with thermoformed aligners across various activation levels. The relatively lower but sustained force levels observed with direct-printed aligners may offer clinical advantages, as light continuous forces are more conducive to effective orthodontic tooth movement. These forces not only enhance biological efficiency but also minimize patient discomfort, thereby optimizing overall treatment outcomes.

Our findings are consistent with those of previous studies examining materials such as Zendura Viva, a multi-layered aligner material. Under simulated clinical conditions involving a 0.2 mm facial malalignment of the upper right central incisor, Zendura Viva exerted an initial force ranging from approximately 0.1 to 0.5 N before aging, with force levels decreasing to less than 50% after 48 hours [20]. The observed decrease in force magnitude can be attributed to changes in the mechanical properties of the material, specifically a decrease in yield stress following thermoforming, which is further exacerbated by storage in artificial saliva [27,28]. Zendura VIVA also displays resilience against the aging process. These factors collectively support Zendura Viva's function in delivering gentle, controlled forces to efficient and comfortable orthodontic tooth alignment.

Conversely, materials such as TA 28 exhibit unique thermomechanical properties that enhance their clinical performance. TA 28 retained its viscoelastic properties at body temperature (37°C), exhibiting flexibility and a shape memory effect that enabled the sustained application of regulated orthodontic forces during repeated loading cycles. This adaptability improves resistance to force decay, thereby maintaining effective force delivery throughout the treatment [13,29]. These thermomechanical characteristics support clinical efficacy by preserving the geometric stability of the aligner and ensuring hygienic maintenance under oral conditions. This combination of flexibility, memory effect, and durability ultimately promotes patient comfort and treatment efficiency by providing consistent, biologically favorable forces over an extended period. Orthodontic aligner materials undergo changes in their mechanical properties when exposed to body temperature and saliva, which affect their efficacy during treatment. At approximately 37°C (body temperature), some materials become less stiff but gain beneficial properties, such as shape memory and viscoelasticity, aiding in maintaining the appropriate force on teeth [30]. This is particularly true for advanced 3D-printed materials, such as TA-28. Conversely, when thermoformed polymers absorb saliva, their strength and ability to resist deformation (yield stress) decrease, leading to a reduction in the force they apply over time. This finding underscores the generally higher force transmission capability of thermoformed multi-layer sheets versus emerging 3D-printed options, although force control and adaptation differ between technologies [13,29].

The present findings corroborate that Zendura Viva exerts significantly greater orthodontic forces than TA28 at both 1° and 2° rotations prior to aging, which is consistent with both descriptive and inferential

analyses. However, artificial aging results in considerable force degradation in both materials, significantly diminishing the force levels and reducing the initial inter-material differences. Notably, while increased rotation angles initially corresponded with higher force output, this effect diminished post-aging, indicating that activation magnitude has a limited impact on long-term force retention for both thermoformed and direct-printed aligners. These results highlight the critical influence of material composition and aging on force delivery, emphasizing the need for clinicians to consider force decay when planning orthodontic treatments with aligners. These insights contribute to optimizing aligner selection and activation strategies to maintain effective force application throughout the treatment duration. Understanding the interplay between mechanical properties, environmental factors, and force delivery profiles is crucial for developing aligners that balance efficacy and patient comfort. Future research focusing on the long-term behavior of emerging aligner materials under intraoral conditions will further enhance the predictability and success of orthodontic treatment using clear aligner therapy.

Although this study offers valuable insights, certain limitations must be acknowledged. The *in vitro* design does not accurately replicate the complex intraoral environment, where biological factors such as the response of the periodontal ligament, occlusal forces, and patient compliance significantly influence the treatment outcomes. FSR sensor films only provide localized, one-dimensional force measurements on a single tooth surface, resulting in higher force values. In-situ calibration not only effectively eliminates persistent structural errors caused by the pre-bending of the thin-film sensor across the canine crown but also addresses these issues comprehensively. However, the rigid boundary conditions imposed by an aligner encasing an anatomical tooth introduce complex micro-domain edge stress concentrations. Although these localized stress concentrations may slightly increase absolute force values, they are consistently present in both thermoformed and direct-printed setups, thereby maintaining the validity of the relative comparative analysis. Furthermore, this study was confined to the rotational movement of the maxillary canines, and the results may not be directly applicable to other types of tooth movements. Additionally, factors such as attachment design and aligner fit were not considered, which may also impact the force delivery [31,32].

Conclusion

This study demonstrated significant differences in force delivery between thermoformed and direct 3D-printed clear aligners during low-degree rotational tooth corrections, with the former initially generating higher forces. Both materials exhibited substantial force degradation following artificial aging, which diminished the initial differences in force magnitude. The degree of rotational activation influenced the initial force output but had a limited impact on force retention after aging. These findings highlight the critical role of material properties and aging effects in orthodontic force sustainability, underscoring the importance of considering force decay in clinical treatment planning using clear aligners.

Clinically, these results emphasize that clinicians must carefully consider the choice of aligner material and the effects of aging when planning orthodontic treatments involving rotational tooth movements. Since thermoformed aligners initially deliver higher forces but experience significant force decay similar to direct 3D-printed aligners after aging, treatment protocols should account for this reduction in force over time to maintain effective tooth movement. The limited impact of rotational activation magnitude on long-term force retention suggests increasing activation angles may not compensate for force loss due to material aging. Therefore, clinicians should monitor force levels throughout treatment and potentially adjust activation strategies or replacement intervals to ensure sustained orthodontic efficacy. Understanding the distinct force delivery profiles of different aligner materials can guide personalized treatment planning to optimize outcomes and patient comfort. The novel application of the FSR402 Sensor provides a reliable approach for quantifying aligner forces, contributing valuable insights for optimizing aligner design and activation protocols for improved orthodontic outcomes.

References

1. Tamer I, Oztas E, Marsan G. Orthodontic Treatment with Clear Aligners and The Scientific Reality Behind Their Marketing: A Literature Review. *Turk J Orthod.* 32(4), 241-246 (2019). [doi:10.5152/turkorthod.2019.18083](#)
2. Almogbel A. Clear Aligner Therapy: Up to date review article. *J Orthodont Sci.* 12(1), 37 (2023). [doi:10.4103/jos.jos_30_23](#)
3. Niu C, Li D, Zhang Y, et al. Prospects for 3D-printing of clear aligners: a narrative review. *Front Mater.* 11, 1438660 (2024). [doi:10.3389/fmats.2024.1438660](#)
4. Tartaglia GM, Mapelli A, Maspero C, et al. Direct 3D Printing of Clear Orthodontic Aligners: Current State and Future Possibilities. *Materials.* 14(7), 1799 (2021). [doi:10.3390/ma14071799](#)
5. Li N, Wang C, Yang M, et al. Effects of different tooth movement patterns and aligner thicknesses on maxillary arch expansion with clear aligners: a three-dimensional finite element study. *Front Bioeng Biotechnol.* 12, 1424319 (2024). [doi:10.3389/fbioe.2024.1424319](#)
6. Bae BG, Kim YH, Lee GH, et al. A study on the compressive strength of three-dimensional direct printing aligner material for specific designing of clear aligners. *Sci Rep.* 15(1), 2489 (2025). [doi:10.1038/s41598-025-86687-4](#)
7. Rossini G, Schiaffino M, Parrini S, Sedran A, Deregibus A, Castroflorio T. Upper Second Molar Distalization with Clear Aligners: A Finite Element Study. *Applied Sciences.* 10(21), 7739 (2020). [doi:10.3390/app10217739](#)
8. Sultanoğlu E, Gürel HG, Gülyurt M. The Effects of Different Attachment Types and Positions on Rotation Movement in Clear Aligner Treatments: A Finite Element Analysis. *Cureus.* 16(8), e66273 (2024). [doi:10.7759/cureus.66273](#)
9. Cortona A, Rossini G, Parrini S, Deregibus A, Castroflorio T. Clear aligner orthodontic therapy of rotated mandibular round-shaped teeth: A finite element study. *The Angle Orthodontist.* 90(2), 247-254 (2019). [doi:10.2319/020719-86.1](#)
10. Pede K, Shetty P, Ranjan A, Khan W, Patil H, Mishra H. Evaluation of effects of different sizes and shapes of attachments during rotation, tipping, and torquing in clear aligner therapy - A finite element study. *Journal of orthodontic science.* 13(1) pages (2024). [doi:10.4103/jos.jos_199_23](#)
11. Zamani NSM, Ashari A, Ali SHM, et al. Distributed Force Measurement and Mapping Using Pressure-Sensitive Film and Image Processing for Active and Passive Aligners on Orthodontic Attachments. *IEEE Access.* 10, 52853-52865 (2022). [doi:10.1109/access.2022.3175210](#)
12. Alhafi ZM, Hajeer MY, Alam MK, Jaber ST. Quality and stability of orthodontic treatment outcomes with clear aligners versus fixed appliances: a systematic review and meta-analysis. *European journal of orthodontics.* 47(6) cja091 (2025). [doi:10.1093/ejo/cja091](#)
13. Cenzato N, Di Iasio G, Martin Carreras-Presas C, Caprioglio A, Del Fabbro M. Materials for Clear Aligners—A Comprehensive Exploration of Characteristics and Innovations: A Scoping Review. *Applied Sciences.* 14(15), 6533 (2024). [doi:10.3390/app14156533](#)
14. Barone S, Paoli A, Neri P, Razzionale AV, Giannese M. Mechanical and Geometrical Properties Assessment of Thermoplastic Materials for Biomedical Application. In: B. Eynard et al. (eds.), *Advances on Mechanics, Design Engineering and Manufacturing, Lecture Notes in Mechanical Engineering*, Springer; 437-446 (2016). [doi:10.1007/978-3-319-45781-9_44](#)
15. Szczesio-Włodarczyk A, Fronczek M, Ranozek-Soliwoda K, Grobelny J, Sokolowski J, Bociong K. The First Step in Standardizing an Artificial Aging Protocol for Dental Composites—Evaluation of Basic Protocols. *Molecules.* 27(11), 3511 (2022). [doi:10.3390/molecules27113511](#)
16. Kuntz L, Aranda L, Rapin C, Canceill T, Vande Vannet B, Fawaz P. Effects of aging on the tensile strength and surface condition of orthodontic aligners: a comparative study of five models. *European journal of orthodontics.* 46(6) cjae063 (2024). [doi:10.1093/ejo/cjae063](#)
17. Siotou K, Chountalas T, Katsavrias A, et al. The Mechanical Properties of Orthodontic Aligners of Clear Aligner After Intraoral Use in Different Time Periods. *Orthod Craniofac Res.* 28(2), 253-260 (2024). [doi:10.1111/ocr.12867](#)
18. Bleilöb M, Welte-Jzyk C, Knöde V, Ludwig B, Erbe C. Biocompatibility of variable thicknesses of a novel directly printed aligner in orthodontics. *Sci Rep.* 15(1) 3279 (2025). [doi:10.1038/s41598-025-85359-7](#)
19. Choi JY, Kim H, Kim SH, et al. Mechanical and viscoelastic properties of a temperature-responsive photocurable resin for 3D printed orthodontic clear aligners. *Sci Rep.* 15(1) 23530 (2025). [doi:10.1038/s41598-025-93026-0](#)
20. Elshazly TM, Bourauel C, Ismail AM, et al. Effect of thermomechanical ageing on force transmission by orthodontic aligners made of different thermoformed materials: An experimental study. *Orthod Craniofac Res.* S2, 113-119 (2024). [doi:10.1111/ocr.12825](#)
21. Golkhani B, Weber A, Keilig L, Reimann S, Bourauel C. Variation of the modulus of elasticity of aligner foil sheet materials due to thermoforming. *J Orofac Orthop.* 83(4), 233-243 (2021). [doi:10.1007/s00056-021-00327-w](#)
22. El Idrissi I, El Mabrouk K, Zaoui F, Benyahia H. Performance of orthodontic aligners in the aging process: systematic review and *in vitro* study. *J Orthodontie Française.* 92(3), 335-341 (2021). [doi:10.1684/orthodfr.2021.57](#)
23. Diedrich P. Biomechanical principles of orthodontic movement of teeth with periodontal involvement. *Deutsche Zahnärztliche Zeitschrift.* 45(2), 78-81 (1990).
24. Ren Y, Maltha J, Kuijpers-Jagtman AM. Optimum force magnitude for orthodontic tooth movement: a systematic literature review. *The Angle orthodontist.* 73(1), 86-92 (2015). [doi:10.1043/0003-3219\(2003\)073<0086:ojmfot>2.0.co;2](#)
25. Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C. Forces and moments generated by removable thermoplastic aligners: Incisor torque, premolar derotation, and molar distalization. *American Journal of Orthodontics and Dentofacial Orthopedics.* 145(6), 728-736 (2014). [doi:10.1016/j.ajodo.2014.03.015](#)
26. Cremonini F, Pancari C, Bruculeri L, Karami Shabankare A, Lombardo L. Force Expressed by 3D-Printed Aligners with Different Thickness and Design Compared to Thermoformed Aligners: An *in vitro* Study. *Applied Sciences.* 15(6), 2911 (2025). [doi:10.3390/app15062911](#)
27. Gornig DC, Maletz R, Otl P, Warkentin M. Influence of artificial aging: mechanical and physicochemical properties of dental composites under static and dynamic compression. *Clin Oral Invest.* 26(2), 1491-1504 (2021). [doi:10.1007/s00784-021-04122-0](#)
28. Ryu JH, Kwon JS, Jiang HB, Cha JY, Kim KM. Effects of thermoforming on the physical and mechanical properties of thermoplastic materials for transparent orthodontic aligners. *Korean J Orthod.* 48(5), 316 (2028). [doi:10.4041/kjod.2018.48.5.316](#)
29. Atta I, Bourauel C, Alkabani Y, et al. Physicochemical and mechanical characterisation of orthodontic 3D printed aligner material made of shape memory polymers (4D aligner material). *Journal of the Mechanical Behavior of Biomedical Materials.* 150, 106337. [doi:10.1016/j.jmbbm.2023.106337](#)
30. Lombardo L, Martines E, Mazzanti V, Arreghini A, Mollica F, Siciliani G. Stress relaxation properties of four orthodontic aligner materials: A 24-hour *in vitro* study. *The Angle Orthodontist.* 87(1), 11-18 (2016). [doi:10.2319/113015-813.1](#)
31. McKay A, McCray J, Bankhead B, et al. Forces and moments generated during extrusion of a maxillary central incisor with clear aligners: an *in vitro* study. *BMC Oral Health.* 23(1), 495 (2023). [doi:10.1186/s12903-023-03136-2](#)
32. Sayahpour B, Zinelis S, Polychronis G, et al. Effects of intraoral aging on mechanical properties of directly printed aligners vs. thermoformed aligners: an *in vivo* prospective investigation. *European Journal of Orthodontics.* 46(1), cjad063 (2024). [doi:10.1093/ejo/cjad063](#)