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Original Article

Initial Assessment of the Shape Recovery Behavior of Orthodontic Aligners Made from Shape Memory Polymers: A Typodont-Based Study

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ABSTRACT

This study investigated the use of shape memory polymers (SMPs) as an innovative material for orthodontic aligners to overcome the limitations of conventional multi-step staging. The research evaluated the ability of SMPs to recover their original shape and induce tooth movement when activated, using a typodont model as a preliminary in vitro test. The goal was to achieve a 1.9 mm movement of an upper central incisor using a single aligner through successive activation steps. A custom typodont with a movable central incisor was digitally scanned, and 3D-printed resin models were produced with orthodontic software. Seven aligners were then thermoformed from ClearX SMP sheets over the resin models. Each aligner's capacity to reposition the central incisor was assessed on the typodont, and scans were taken after each step to quantify the movement via digital superimposition. The overall tooth correction reached approximately 93% (1.76 mm). Stepwise measurements showed 0.94 ± 0.04 mm after the initial reforming, 0.66 ± 0.07 mm following the first activation, and 0.15 ± 0.10 mm after the second activation. These results indicate that SMP-based aligners may offer a promising approach for aesthetic orthodontic treatments in the future.

Keywords: Digital workflow, Orthodontics, Clear aligners, Smart polymers, Typodont, Orthodontic appliance

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Introduction

Fixed orthodontic appliances, such as braces and archwires, remain the cornerstone of conventional orthodontic treatment. Nevertheless, patients often experience discomfort, including oral mucosal irritation and tooth soreness, as well as challenges in maintaining proper oral hygiene. Additionally, the aesthetic limitations of buccal braces lead some patients—particularly adults—to decline treatment [1–3]. To address these concerns and meet the growing demand for more aesthetic solutions, alternative approaches have been developed, including ceramic or composite braces, lingual braces, and clear orthodontic aligners [4].

Clear aligners consist of a series of thin, transparent, custom-fitted, removable plastic trays designed to progressively move teeth into the desired alignment. They are typically worn for at least 20 hours per day and replaced approximately every two weeks [5]. Each aligner achieves limited tooth movement, generally about 0.2–0.3 mm for translations and 1°–3° for rotations per tooth [6]. These aligners can be fabricated from a variety of polymers, including polyethylene terephthalate glycol (PETG) [5] and polyurethane [7]. Studies have shown that clear aligners can reduce treatment duration and chair time in mild to moderate cases [8], making them an effective and practical alternative to traditional fixed braces [9, 10]. However, their clinical application is still restricted by the stepwise staging required for tooth movement [5, 6, 8, 11], motivating research efforts aimed at enhancing aligner materials, force systems, movement staging, and treatment planning [12].

Recent interdisciplinary research has focused on developing materials capable of actively participating in treatment, known as smart or stimuli-responsive materials. These materials respond predictably to external triggers—such as thermal, electrical, or magnetic stimuli—producing controlled, repeatable effects [13, 14]. A subset of these, shape memory materials, can change their macroscopic form when appropriately stimulated and retain a temporary shape until activation prompts recovery to their original configuration [15, 16].

Shape memory polymers (SMPs), a category of smart shape memory materials, exhibit this active behavior [16, 17]. The shape memory effect in SMPs relies on two critical components: a stable polymer network that defines the original shape, and a reversible switching segment that locks in the temporary shape [18, 19]. SMPs offer numerous advantages, including large elastic deformation capacity, low cost, light weight, manufacturability, tunable properties, excellent chemical stability, and high biocompatibility [20], making them attractive for diverse applications, particularly in biomedical devices [21].

Thermo-responsive SMPs are especially promising for orthodontics due to their combination of functional performance and aesthetic appeal. Beyond their transparency and visual acceptability, SMPs provide intrinsic shape recovery forces, which could enhance aligner performance by enabling self-activating tooth movement [13, 22]. In an initial study, Jung *et al*. [22] demonstrated that shape memory polyurethane wires could correct tooth position on a typodont model within one hour when heated above 50 °C. Although several patents propose using smart polymers for aligner fabrication [23–25], empirical studies evaluating their clinical potential remain limited [13].

The present study is a preliminary in vitro investigation of orthodontic aligners made from thermo-responsive SMPs. By harnessing the shape recovery forces activated through thermal stimuli, the study evaluated the potential to move a tooth on a typodont model using a single aligner. The objective was to overcome the staging limitations of conventional aligners, potentially reducing the number of aligners required per treatment, saving time and cost, minimizing plastic usage, and ultimately lowering overall treatment expenses.

Materials and Methods

Specimen preparation

Before conducting the main experiments, preliminary tests were carried out to identify the optimal conditions for thermoforming and reforming the SMP sheets, including temperature, pressure, and processing duration, to ensure effective shape recovery. Multiple trial runs were performed at each stage to fine-tune these parameters for consistent and reproducible results.

A custom typodont model (model T) was constructed using acrylic teeth (Frasaco, Teltnag, Germany) and resin (Technovit 4004, Kulzer, Wehrheim, Germany). The upper left central incisor was made movable by embedding it in pink wax (Set Up Dental Wax, Cavex, Haarlem, the Netherlands), while all remaining teeth were fixed in resin **(Figure 1)**. The fully aligned model was scanned initially (scan 0) with a 3D laboratory scanner (D2000, 3Shape, Copenhagen, Denmark), and the digital model was segmented using Ortho Analyzer software (v. 2012-1, 3Shape, Copenhagen, Denmark). A palatal malposition of 1.9 mm was digitally designed for the upper left central incisor, and an additional intermediate model was generated with a 1.2 mm malposition, corresponding to a 0.7 mm step in correction **(Table 1)**.

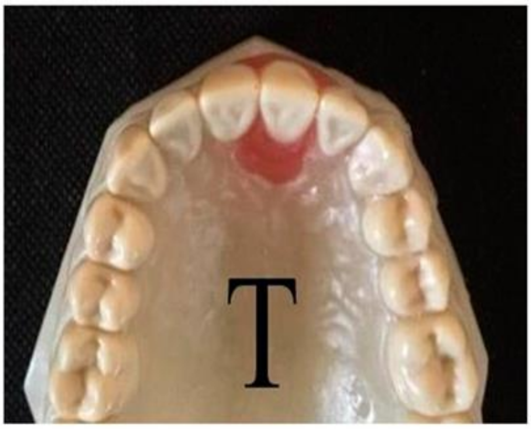

Figure 1. Custom-designed typodont model of the upper dental arch featuring a movable left central incisor (Model T).

Table 1. List of models and scans utilized in the study

Type	Name	Description	Purpose
Models	Model T	Typodont with a movable upper left central incisor	Scanned in fully aligned position (Scan 0) for software manipulation; the movable

			incisor served to evaluate tooth movement achieved via aligner shape recovery.
	Model 0	3D-printed resin model with complete malposition (1.9 mm)	Served as a template for a guiding splint to reposition the typodont's central incisor to the zero position.
	Model 1	3D-printed resin model with partial malposition (1.2 mm), representing partial correction (0.7 mm)	Used for reforming the aligners.
	Model 2	3D-printed resin model with full correction (1.9 mm)	Utilized for thermoforming the aligners.
	Scan 0	Scan of the fully aligned typodont	Used for software manipulation and for generating Models 0, 1, and 2.
	Scan 1	Scan of the typodont after using the guiding splint to move the central incisor into full malposition	Should ideally match the shape of Model 0.
Scans	Scan 2	Scan after movement of the central incisor using the reformed aligner	Used for superimposition to measure the extent of tooth movement.
	Scan 3	Scan after movement of the central incisor using the aligner following the first activation cycle	Used for superimposition and measurement of tooth movement.
	Scan 4	Scan after movement of the central incisor using the aligner following the second activation cycle	Used for superimposition and measurement of tooth movement.

The study utilized three digital models—two representing malpositioned teeth and one fully aligned—which were saved as STL files and 3D printed **(Figure 2)** using Dentona Optiprint model resin (Dentona AG, Dortmund, Germany) on an Asiga Max 3D printer (SCHEU-DENTAL GmbH, Iserlohn, Germany). These included Model 0, showing a 1.9 mm malposition (no correction), Model 1 with a 1.2 mm malposition (0.7 mm corrected), and Model 2, which was fully aligned (complete 1.9 mm correction). To consistently reposition the movable central incisor to the malaligned state for repeated measurements, a guiding splint was fabricated from a 1.5 mm thick thermoplastic sheet (Erkodur, Erkodent Erich Kopp, Pfalzgrafenweiler, Germany) by thermoforming over Model 0. The splint's thickness ensured sufficient rigidity to maintain precise positioning during testing.

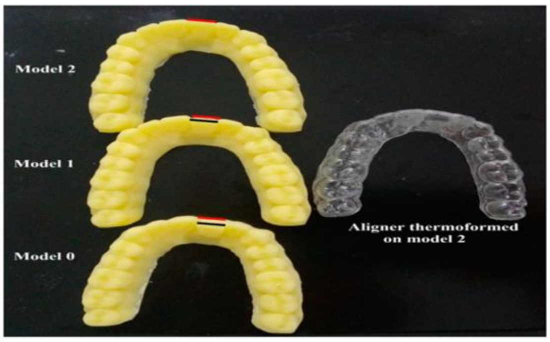

Figure 2. 3D-printed models showing different malpositions of the central incisor along with a ClearX thermoformed aligner.

To correct a 1.9 mm malposition using a single aligner instead of three sequential aligners, the procedure involved consecutive thermoforming, reforming, and two activation cycles. Initially, a clear aligner was fabricated on the fully aligned model (Model 2) using a 0.76 mm ClearX shape memory sheet (Kline-Europe GmbH, Düsseldorf, Germany). The sheet was heated to 120 °C for 30 seconds and pressed over the model at 4 bar using a Ministar thermoforming device (SCHEU-DENTAL GmbH, Iserlohn, Germany), following the manufacturer's guidelines. After removal, the aligner was trimmed and finished.

Subsequently, the aligner underwent a reforming step on Model 1, which represented a partially corrected stage (1.2 mm malalignment). This ClearX-specific process reshapes the aligner to fit an intermediate correction step. In practice, the thermoformed aligner from Model 2 was immersed in warm water at 85 °C for 20 seconds and then immediately pressed over Model 1 using the same thermoforming device to adapt to the intermediate shape. Effectively, the aligner experienced two heating cycles: the first to establish its original shape during thermoforming, and the second to temporarily reshape it for the partial correction stage.

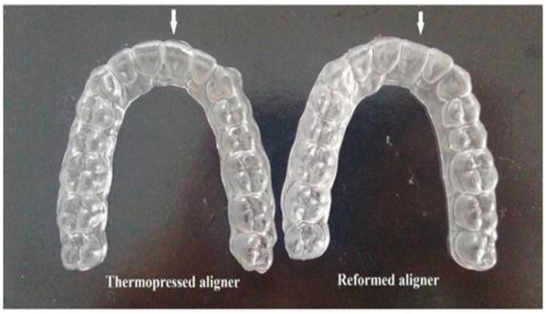

Figure 3. Thermoformed aligner on Model 2 and the reformed aligner on Model 1.

Evaluation of shape memory-induced tooth movement on the typodont model

To begin, the wax surrounding the upper left central incisor in Model T was softened. Using the guiding splint, the tooth was repositioned to match the alignment of Model 0. The typodont was then immersed in a 5 °C water bath for 10 minutes to allow the wax to solidify, ensuring it could support the aligner without distortion [7]. A scan was taken at this stage (Scan 1).

Next, the reformed aligner was placed onto Model T, and the assembly was submerged in a 50 °C water bath for 10 minutes. The water level was carefully adjusted to just cover the wax below the aligner margin, minimizing unintended activation of the aligner's shape memory effect while softening the wax enough to permit movement of the embedded tooth. Afterward, the model was returned to a 5 °C water bath for 10 minutes to harden the wax prior to aligner removal, followed by another scan (Scan 2).

To trigger the shape memory recovery, the aligner underwent its first activation cycle using a ClearX Aligner Booster device (v. 2.1, Kline-Europe GmbH, Düsseldorf, Germany). This electrically programmed device, controlled via the ClearX Mobil App (v. 1.1.4, available for iOS and Android), heats the aligner in water to enable it to return to its original shape. For the first activation, the aligner was submerged in 67 °C water for 10 minutes. The activated aligner was then positioned on Model T and the assembly placed in a 50 °C water bath for 10 minutes, again adjusting the water level to just below the aligner margin. Following this, the typodont was scanned (Scan 3).

The aligner was subsequently subjected to a second activation cycle under the same conditions. After activation, it was placed back on Model T, submerged in the 50 °C water bath for 10 minutes, and the model was scanned once more (Scan 4) to evaluate the cumulative tooth movement.

Figure 4. ClearX booster device, controlled through a mobile app, used to programmatically activate the ClearX aligners.

The procedure was repeated seven times, using a fresh aligner for each trial (n = 7) to ensure reproducibility and reliability of the results. New wax was applied for every repetition to prevent changes in material properties caused by previous heating and cooling cycles. Before each trial, the initial malposition of the upper left central incisor in Model T was rescanned (Scan 1) after repositioning with the guiding splint, ensuring accurate baseline measurements for each new aligner.

Digital model evaluation

For every aligner, four sequential 3D scans of Model T were captured to monitor tooth movement **(Figure 5)**: the first scan recorded the initial malalignment after using the guiding splint (Scan 1); the second scan followed placement of the reformed aligner (Scan 2); the third scan captured the tooth position after the aligner underwent its first activation cycle (Scan 3); and the fourth scan documented changes following the second activation cycle (Scan 4).

a)

b)

c)

d)

Figure 5. Model T at various stages prior to scanning throughout the treatment process.

The 3D scans were overlaid using Ortho Analyzer software to quantify tooth movement in millimeters at each stage, both relative to the initial position recorded in Scan 1 and relative to the preceding step **(Figure 6)**. An overview of all models and scans employed in this research is provided in **Table 1**. Additionally, a schematic representation of the key steps involved in the ClearX method is presented in **Figure 7**.

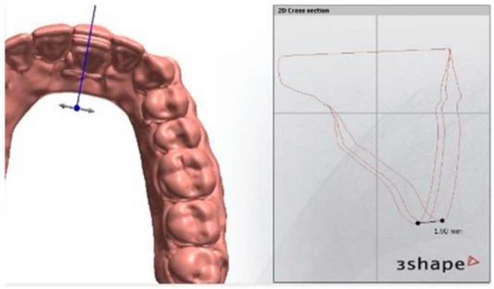

Figure 6. Overlay of typodont scans performed with 3Shape Ortho Analyzer software to assess and quantify tooth movement at each stage.

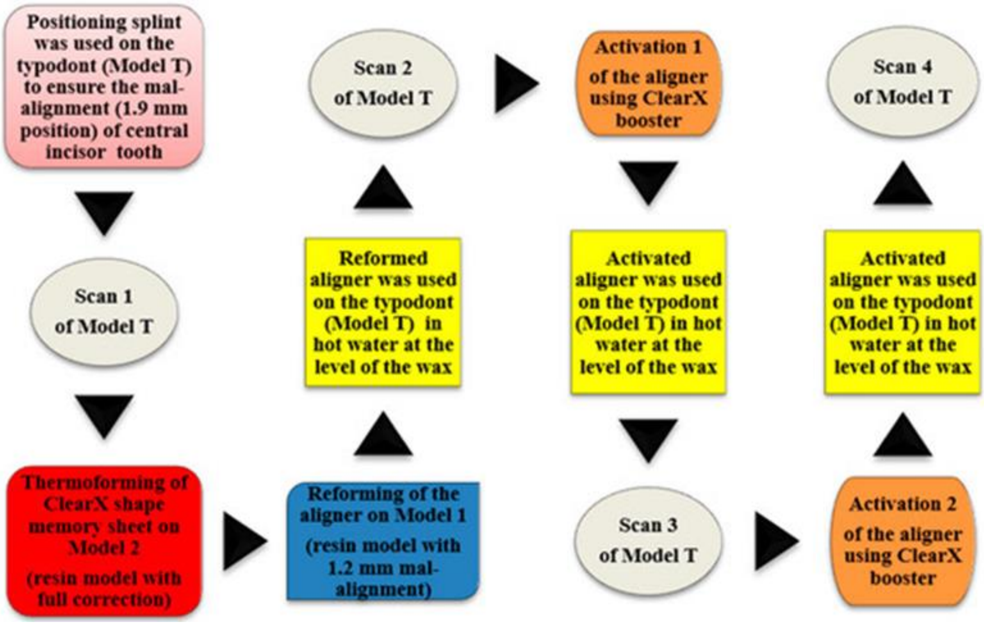

Figure 7. Diagram illustrating the key steps of the ClearX method.

Results and Discussion

Significant corrective movements of the upper left central incisor were observed on the typodont at each stage. Placement of the reformed aligner resulted in an additional 0.94 ± 0.04 mm of tooth movement, corresponding to an average of 49.47 percent of the total planned correction (Scan 2 vs. Scan 1). The first activation cycle contributed a further 0.66 ± 0.07 mm, representing 34.74% of the overall planned movement (Scan 3 vs. Scan 2), while the second activation cycle produced an additional 0.15 ± 0.10 mm, accounting for 7.89 percent of the total planned correction (Scan 4 vs. Scan 3). These findings are summarized in **Tables 2 and 3** and illustrated in **Figure 8**.

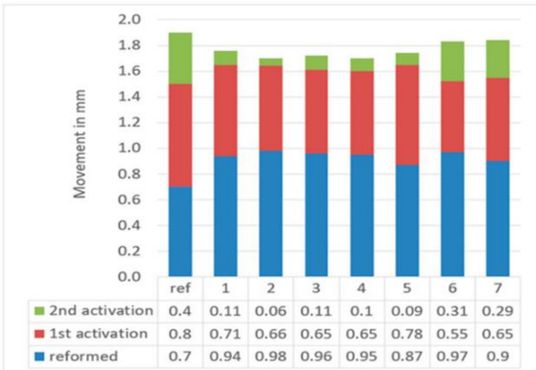

Figure 8. Step-by-step movement of the upper left central incisor on a typodont model as achieved using seven separate ClearX aligners.

Table 2. Average values and standard deviations (SD) for cumulative tooth movement (total correction, TC) of the upper left central incisor, calculated by overlaying each step's scan on the initial malposition scan; incremental movement (added correction, AC) determined by comparing each step to the preceding one; and the corresponding efficiency of correction provided by the ClearX aligners expressed as a percentage.

	Scan 1 vs. 2		**Scan 1 vs. 3**		**Scan 1 vs. 4**	
	TC	**AC**	**TC**	**AC**	**TC**	**AC**
Planned movement	0.70	0.70	1.50	0.80	1.90	0.40
Aligner 1	0.94	0.94	1.65	0.71	1.76	0.11
Aligner 2	0.98	0.98	1.64	0.66	1.70	0.06
Aligner 3	0.96	0.96	1.61	0.65	1.72	0.11
Aligner 4	0.95	0.95	1.60	0.65	1.70	0.10
Aligner 5	0.87	0.87	1.65	0.78	1.74	0.09
Aligner 6	0.97	0.97	1.52	0.55	1.83	0.31
Aligner 7	0.90	0.90	1.55	0.65	1.84	0.29
Mean (mm)	0.94	0.94	1.60	0.66	1.76	0.15
SD	0.04	0.04	0.07	0.07	0.10	0.10
Correction % (divided by 1.9 mm total movement)	49.47%	49.47%	84.21%	34.74%	92.63%	7.59%

Table 3. Numerical values and percentages of shape memory recovery components.

Recovery	**Added Movement**	**% Recovery of Shape Memory Component Per Step (Divided by Total 1.2 mm)**	**% Recovery of Activated Shape Memory Component Per Step (Divided by Total 0.96 mm)**
Spontaneous	0.24 mm	20%	
First activation	0.66 mm	55%	68.75%
Second activation	0.15 mm	12.5%	15.63%

The primary goal behind innovations and advancements in the field of orthodontic aligners is to simplify both the fabrication and treatment process while reducing overall treatment time and costs. One of the most significant developments in recent decades has been the integration of digital technologies into aligner fabrication [1, 3]. In parallel, the exploration of novel materials for aligners has attracted considerable research attention [23–25]. Selecting an appropriate material, however, is challenging, as it requires careful consideration of both biocompatibility and biomechanical properties. Moreover, developing a clinically applicable method to evaluate a material's shape memory characteristics remains complex. Consequently, extensive in vitro investigations are essential before any clinical application can be considered.

In this study, the potential of smart polymers—specifically thermo-responsive shape memory polymers (SMPs)—was explored for orthodontic aligner fabrication. These materials can maintain multiple shapes and revert to their original configuration upon exposure to an appropriate thermal stimulus or a sequence of stimuli [26].

The ClearX system sheets, produced by Kline Europe GmbH, are reported to be thermo-responsive shape memory polyurethanes. They are designed to return to their original thermoformed shape following a reforming step when thermally activated at specific temperatures for a defined duration. This stepwise shape recovery characteristic makes the material promising for orthodontic applications, potentially allowing a single aligner to replace three conventional sequential aligners. This could reduce the number of aligners needed per treatment, resulting in cost and time savings, particularly for complex orthodontic cases such as molar distalization or severe open/deep bite corrections [27–29].

Additionally, the method examined in this study is compatible with CAD/CAM systems, which are increasingly utilized across multiple dental disciplines, including restorative dentistry, prosthodontics, and orthodontics. CAD/CAM workflows enable fully digital procedures—from impression to final appliance—with high clinical reliability [30] and positive patient feedback [31].

In this study, an overall correction efficiency of approximately 92.63% was achieved on the typodont using a single reforming step followed by two activation cycles. The shape memory behavior of SMPs depends not only on the polymer's chemical composition but also on processing conditions, making careful control of these parameters crucial for achieving consistent results [32]. Accordingly, a series of sensitivity tests were conducted before the main experiment to optimize the variables that influence shape recovery, including temperature, moisture, and duration of each step. From thermoforming through reforming to activation, all steps were highly sensitive. Activation of the shape memory effect was performed using the ClearX booster device **(Figure 4)**. After sensitivity testing, the first activation cycle was found to induce roughly 65% of the aligner's shape recovery, while the second cycle accounted for the remaining 35%.

The underlying mechanism of shape memory in SMPs involves a dual-domain system with distinct glass transition or melting temperatures. At ambient conditions, one domain remains rigid and elastic, while the other is soft and ductile [33]. In thermo-responsive SMPs, shape memory operates through reversible activation and deactivation of polymer chain mobility in the switching segments, triggered above and below the material's transition temperature (T trans), which may correspond to either the glass transition temperature (Tg) or melting temperature (Tm) [13, 19, 34]. When T trans is reached, the deformed SMP exhibits elastic properties and returns to its original shape, generating forces capable of inducing tooth movement [35].

SMPs are capable of adopting multiple temporary shapes due to their broad range of shape recovery temperatures and the ability to endure substantial recoverable strain [18, 26]. Shape memory polyurethane resins contain both polar and non-polar molecules that form microdomains of hard and soft segments. The hard segments provide structural strength, while the soft segments contribute flexibility and toughness, enabling the production of resilient orthodontic aligners capable of sustaining tooth movement over longer durations [32, 36]. Furthermore, polyurethane resins are resistant to staining and plaque accumulation, maintaining clarity under oral conditions; however, their hydrogen bonding makes them sensitive to moisture, which likely influenced the performance of ClearX aligners during the reforming and activation steps [36–38].

The reformed aligner was theoretically intended to produce a corrective movement of 0.7 mm, with the first thermal activation cycle expected to recover approximately 55–65% of the programmed shape change and the second activation cycle contributing 25–35%, depending on the planned tooth displacement. Interestingly, the reformed aligners in this study produced an average movement of 0.94 mm, exceeding the planned 0.7 mm **(Table 2 and Figure 8)**. This additional displacement may be explained by spontaneous recovery during stress release or partial activation induced by the 50 °C water bath used to soften the wax, resulting in approximately 0.24 mm of extra movement, equivalent to 20% of the total shape memory component.

After the first activation cycle, the aligners generated an additional average movement of 0.66 mm, representing 55% of the planned shape memory correction and yielding a cumulative movement of 1.6 mm (84.2% of the total 1.9 mm planned movement). The second activation cycle added 0.15 mm on average, or 12.5% of the planned shape memory movement, leading to a final mean displacement of 1.75 mm, corresponding to 92.63% of the intended correction.

According to the ClearX system, the remaining 7–8% of movement is intended to be achieved by the subsequent aligner, referred to as the recurrent aligner. This allows for any incomplete tooth movement to be corrected: each new aligner first ensures that prior movements are completed before delivering additional activation.

The observed consistency across all seven specimens indicated reliable behavior of the SMP material. Nevertheless, this study is a preliminary in vitro investigation, serving as a proof-of-concept rather than definitive clinical evidence. The typodont model used wax as a substitute for periodontal tissues, yet natural tooth movement involves complex biological remodeling of the periodontium under orthodontic forces [39]. Additionally, only a single tooth was moved while the remaining teeth were fixed in resin, which does not fully replicate clinical scenarios. Other real-life factors, such as exposure to hot foods or beverages, which could inadvertently trigger aligner activation, were not addressed. Furthermore, the mechanical properties of the aligners and the forces generated by shape memory recovery require thorough evaluation in future studies.

Conclusion

The study demonstrated that clear aligners made from shape memory polymers (SMPs) can induce tooth movement in a typodont model. Achieving shape memory-driven movement requires specific heat treatments above the material's transition temperature. These findings suggest that SMP-based aligners could represent a promising future option for aesthetic orthodontic treatment, offering the potential for more efficient and streamlined therapy.

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Conflict of Interest: None

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Ethics Statement: None

References

1. Ojima K, Kau CH. A perspective in accelerated orthodontics with aligner treatment. Semin Orthod. 2017;23(1):76–82.
2. Boyd RL. Esthetic orthodontic treatment using the Invisalign appliance for moderate to complex malocclusions. J Dent Educ. 2008;72(8):948–67.
3. Phan X, Ling PH. Clinical limitations of Invisalign. J Can Dent Assoc. 2007;73(3):263–6.
4. Mehta F, Mehta S. Aligners: The rapidly growing trend in orthodontics around the world. Indian J Basic Appl Med Res. 2014;3(4):402–9.
5. Thukral R, Gupta A. Invisalign: Invisible orthodontic treatment—A review. J Adv Med Dent Sci Res. 2015;3(5):S42–4.
6. Elkholy F, Schmidt F, Jäger R, Lapatki BG. Forces and moments delivered by novel, thinner PET-G aligners during labiopalatal bodily movement of a maxillary central incisor: An in vitro study. Angle Orthod. 2016;86(6):883–90.
7. Momtaz P. The effect of attachment placement and location on rotational control of conical teeth using clear aligner therapy. UNLV Theses, Dissertations, Professional Papers, and Capstones. 2016. Available from: https://digitalscholarship.unlv.edu/thesesdissertations/2712/
8. Zheng M, Liu R, Ni Z, Yu Z. Efficiency, effectiveness and treatment stability of clear aligners: A systematic review and meta-analysis. Orthod Craniofac Res. 2017;20(3):127–33.
9. 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. Am J Orthod Dentofacial Orthop. 2014;145(6):728–36.
10. Simon M, Keilig L, Schwarze J, Jung BA, Bourauel C. Treatment outcome and efficacy of an aligner technique—Regarding incisor torque, premolar derotation and molar distalization. BMC Oral Health. 2014;14(1):68.
11. Elkholy F, Schmidt F, Jäger R, Lapatki BG. Forces and moments applied during derotation of a maxillary central incisor with thinner aligners: An in-vitro study. Am J Orthod Dentofacial Orthop. 2017;151(3):407–15.
12. Morton J, Derakhshan M, Kaza S, Li C. Design of the Invisalign system performance. Semin Orthod. 2017;23(1):3–11.
13. Bruni A, Serra FG, Deregibus A, Castroflorio T. Shape-memory polymers in dentistry: Systematic review and patent landscape report. Materials. 2019;12(14):2216.
14. Lendlein A, Kelch S. Shape-memory polymers. Angew Chem Int Ed. 2002;41(12):2034–57.
15. Sun L, Huang W, Ding Z, Zhao Y, Wang C, Purnawali H, et al. Stimulus-responsive shape memory materials: A review. Mater Des. 2012;33(1):577–640.
16. Lendlein A. Progress in actively moving polymers. J Mater Chem. 2010;20(16):3332–4.
17. Meng H, Li G. A review of stimuli-responsive shape memory polymer composites. Polymer. 2013;54(9):2199–221.
18. Huang W, Ding Z, Wang C, Wei J, Zhao Y, Purnawali H. Shape memory materials. Mater Today. 2010;13(9):54–61.
19. Voit W, Ware T, Dasari RR, Smith P, Danz L, Simon D, Barlow S, Marder SR, Gall K. High-strain shape-memory polymers. Adv Funct Mater. 2009;20(2):162–71.
20. Huang WM, Yang B, Fu YQ. Polyurethane shape memory polymers. Boca Raton: CRC Press; 2011.
21. Baudis S, Behl M, Lendlein A. Smart polymers for biomedical applications. Macromol Chem Phys. 2014;215(21):2399–402.
22. Jung YC, Cho JW. Application of shape memory polyurethane in orthodontic. J Mater Sci Mater Med. 2010;21(8):2881–6.
23. Silverman E, Cohen M. Orthodontic appliance. US Patent US3461559A. 1969 Aug 19.
24. Choi Y, Kim KT. Orthodontic appliance by using a shape memory polymer. US Patent US20050003318A1. 2005 Jun 1.
25. Lai ML, Rule JD. Orthodontic appliance having continuous shape memory. US Patent US20200315747A1. 2020 Oct 8.
26. Xie T. Tunable polymer multi-shape memory effect. Nat Cell Biol. 2010;464(7288):267–70.

27. Caruso S, Nota A, Ehsani S, Maddalone E, Ojima K, Tecco S. Impact of molar teeth distalization with clear aligners on occlusal vertical dimension: A retrospective study. BMC Oral Health. 2019;19(1):1–5.
28. Caruso S, Darvizeh A, Zema S, Gatto R, Nota A. Management of a facilitated aesthetic orthodontic treatment with clear aligners and minimally invasive corticotomy. Dent J. 2020;8(1):19.
29. Harris K, Ojima K, Dan C, Upadhyay M, AlShehri A, Kuo CL, Mu J, Uribe F, Nanda R. Evaluation of open bite closure using clear aligners: A retrospective study. Prog Orthod. 2020;21(1):1–9.
30. Emara A, Sharma N, Halbeisen FS, Msallem B, Thieringer FM. Comparative evaluation of digitization of diagnostic dental cast (plaster) models using different scanning technologies. Dent J. 2020;8(4):79.
31. Sfondrini MF, Gandini P, Malfatto M, Di Corato F, Trovati F, Scribante A. Computerized casts for orthodontic purpose using powder-free intraoral scanners: Accuracy, execution time, and patient feedback. BioMed Res Int. 2018;2018:1–8.
32. Li F, Zhang X, Hou J, Xu M, Luo X, Ma D, Kim BK. Studies on thermally stimulated shape memory effect of segmented polyurethanes. J Appl Polym Sci. 1997;64(8):1511–6.
33. Behl M, Lendlein A. Shape-memory polymers. Mater Today. 2007;10(4):20–8.
34. Liu C, Qin H, Mather PT. Review of progress in shape-memory polymers. J Mater Chem. 2007;17(15):1543–58.
35. Nakasima A, Hu JR, Ichinose M, Shimada H. Potential application of shape memory plastic as elastic material in clinical orthodontics. Eur J Orthod. 1991;13(3):179–86.
36. Jeong HM, Lee SY, Kim BK. Shape memory polyurethane containing amorphous reversible phase. J Mater Sci. 2000;35(7):1579–83.
37. Yen FS, Lin LL, Hong JL. Hydrogen-bond interactions between urethane-urethane and urethane-ester linkages in a liquid crystalline poly(ester-urethane). Macromolecules. 1999;32(9):3068–79.
38. McKiernan RL, Heintz AM, Hsu SL, Atkins EDT, Penelle J, Gido SP. Influence of hydrogen bonding on the crystallization behavior of semicrystalline polyurethanes. Macromolecules. 2002;35(18):6970–4.
39. Bourauel C, Freudenreich D, Vollmer D, Kobe D, Drescher D. Simulation of orthodontic tooth movements. J Orofac Orthop. 1999;60(3):136–51.