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Original Article

Assessment of Shape Recovery in 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 a next-generation material for orthodontic aligners to overcome the stepwise limitations of traditional aligner therapy. The ability of SMPs to return to a predefined shape and drive tooth movement under external stimuli was evaluated using a typodont model prior to clinical testing. The experimental setup aimed to achieve a 1.9 mm correction of an upper central incisor through a single aligner subjected to multiple activation phases. A custom typodont with a movable central incisor was digitally scanned, and corresponding resin models were produced via orthodontic software and 3D printing. Seven ClearX SMP aligners were thermoformed over the aligned resin models and sequentially tested for their repositioning effect on the incisor. After each activation step, scans of the model were superimposed to quantify the movement. The overall correction achieved by the SMP aligners was approximately 93% (1.76 mm), with individual contributions of 0.94 ± 0.04 mm from the reforming step, 0.66 ± 0.07 mm after the first activation, and 0.15 ± 0.10 mm following the second activation. These results indicate that SMP-based aligners may offer a viable and effective approach for aesthetic orthodontic treatment in the future.

Key words: Digital workflow, Orthodontics, Clear aligners, Smart polymers, Typodont, Orthodontic appliance, Dentistry, 3D printers

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Introduction

Fixed orthodontic appliances, including braces and wires, have long been considered the standard for correcting dental misalignments. Despite their effectiveness, these appliances often cause patient discomfort, such as irritation of the oral mucosa and tooth soreness, and they complicate maintaining oral hygiene. Additionally, the aesthetic drawbacks of buccal braces lead some patients—particularly adults—to refuse this treatment option [1-3]. To address the demand for more visually appealing alternatives, several options have been developed, including ceramic or composite braces, lingual braces, and clear aligners [4].

Clear aligners are custom-fitted, thin, transparent, removable devices designed to gradually reposition teeth. Patients are required to wear them for at least 20 hours per day, with aligners typically replaced every two weeks [5]. Each aligner can achieve only limited tooth movement—approximately 0.2–0.3 mm for translations and 1°–3° for rotations per tooth [6]. Various polymers, such as polyethylene terephthalate glycol (PETG) [5] and polyurethane [7], are used to manufacture these aligners [8]. Clinical studies have shown that clear aligners can shorten treatment duration and reduce chair time for mild-to-moderate cases, providing a practical and effective alternative to traditional braces [9–11]. Nevertheless, the sequential, stepwise nature of conventional aligners remains a limiting factor [5, 6, 9, 12], prompting ongoing research to optimize aligner materials, force delivery systems, movement staging, and treatment planning [13].

Recent interdisciplinary research has focused on the development of novel "smart" or stimuli-responsive materials capable of responding predictably to external cues, such as thermal, electrical, or magnetic stimuli [14, 15]. Among these, shape memory materials stand out due to their ability to retain a temporary configuration until activated to return to their original form [16, 17]. Shape memory polymers (SMPs), a subset of these materials, rely on a combination of a stable polymer network defining the original shape and a reversible switching segment that fixes the temporary shape [17–20]. SMPs offer several advantages, including high elastic deformability, low density and cost, ease of fabrication, adjustable physical properties, excellent chemical stability, and biocompatibility, making them attractive for biomedical applications [21, 22].

Thermo-responsive SMPs, in particular, hold promise for orthodontic applications due to their functional and aesthetic properties. Their transparent appearance provides an advantage over conventional aligner materials, while their inherent shape recovery can generate self-actuating forces that may enhance aligner efficiency [14, 23]. In an earlier study, Jung *et al*. [23] demonstrated that shape memory polyurethane wires could correct teeth on a typodont model within one hour when heated above their transition temperature (50 °C). While several patents [24–26] propose the use of smart polymers in aligner fabrication, experimental studies exploring their practical application remain limited [14].

The present study is a preliminary in vitro evaluation of thermo-responsive SMP-based orthodontic aligners. By harnessing the shape recovery forces triggered by thermal stimuli, the aligners were tested for their ability to reposition a tooth on a typodont model. The objective was to overcome the stepwise limitations of conventional aligners, exploring the potential to replace multiple sequential aligners with a single SMP aligner, thereby reducing treatment duration, cost, and plastic consumption.

Material and Methods

Specimens' preparation

Before implementing the main experimental protocol, several preliminary tests were performed to fine-tune the critical parameters, particularly the temperature and pressure for deep-drawing (thermoforming), the subsequent reshaping of the material sheets, and their shape recovery. Optimal processing times were also identified to maximize outcomes within the material's limitations. Essentially, every stage of the study was preceded by multiple trial runs to establish the most effective conditions.

A custom typodont (Model T) was constructed using acrylic teeth (Frasaco, Teltnag, Germany) embedded in 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, Harleem, The Netherlands), while the remaining teeth were stabilized with resin **(Figure 1)**. The fully aligned typodont was scanned (scan 0) with a 3D lab scanner (D2000, 3Shape, Copenhagen, Denmark), and the resulting digital model was segmented using Ortho Analyzer software (v. 2012-1, 3Shape, Copenhagen, Denmark). A palatal displacement of 1.9 mm was digitally introduced for the movable incisor, and an intermediate stage of 1.2 mm displacement (equivalent to a partial 0.7 mm correction) was also created **(Table 1)**.

The three models—the fully aligned version and the two malaligned configurations—were exported as STL files and 3D printed **(Figure 2)** with a photopolymer resin (Dentona Optiprint model, Dentona AG, Dortmund, Germany) using an Asiga Max printer (SCHEU-DENTAL GmbH, Iserlohn, Germany). Model 0 represented the full malalignment (1.9 mm), model 1 had partial alignment (1.2 mm), and model 2 was fully aligned (0 mm malalignment).

To ensure consistent repositioning of the movable incisor during repeated tests, a 1.5 mm thick thermoplastic splint (Erkodur, Erkodent Erich Kopp, Pfalzgrafenweiler, Germany) was thermo-pressed on model 0, providing both an alignment guide and sufficient rigidity.

To achieve the complete 1.9 mm correction in a single aligner, rather than a series of aligners, the process involved sequential thermoforming, reforming, and two activation cycles. A clear aligner was initially fabricated on the fully aligned model (model 2) using a 0.76 mm thick shape-memory sheet (ClearX, Kline-Europe GmbH, Düsseldorf, Germany). Thermoforming was performed with a Ministar device (SCHEU-DENTAL GmbH, Iserlohn, Germany) by heating the sheet to 120 °C for 30 seconds, followed by pressing at 4 bar in accordance with manufacturer instructions. After trimming, the aligner was reformed on model 1 (partial correction) to replicate the intermediate stage. This reforming step involved immersing the aligner in warm water at 85 °C for 20 seconds, followed by immediate pressure adaptation on model 1 using the same thermoforming device. In summary, the aligner underwent one heating cycle to acquire the final shape and a second cycle to achieve a temporary shape for partial correction.

Figure 1. Custom typodont upper arch model (Model T) featuring a movable upper left central incisor

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

Type	Name	Description	Purpose
Models	Model T	Typodont model with a movable upper left central incisor.	Scanned in fully aligned state (Scan 0) for software manipulation; the movable tooth was used to assess the extent of movement achieved via the shape-memory aligner.
	Model 0	3D-printed resin model with complete malalignment (1.9 mm).	Served for fabrication of a guiding splint to reposition the movable incisor to the malaligned starting position.
	Model 1	3D-printed resin model with partial malalignment (1.2 mm, corresponding to a 0.7 mm partial correction).	Used for reforming the aligners to match intermediate tooth positions.
	Model 2	3D-printed resin model representing fully corrected alignment (0 mm malalignment, 1.9 mm total correction).	Used for the initial thermoforming of the aligners.
Scans	Scan 0	Digital scan of the fully aligned typodont.	Basis for software manipulation and production of Models 0, 1, and 2.
	Scan 1	Scan of the typodont after repositioning the movable incisor into the fully malaligned position using the guiding splint.	Should correspond to the geometry of Model 0.
	Scan 2	Scan of the typodont following movement of the central incisor with the reformed aligner.	Used for superimposition and quantification of tooth movement.

Scan 3	Scan of the typodont after the first activation cycle with the aligner.	Used for superimposition and measurement of tooth displacement.
Scan 4	Scan of the typodont after the second activation cycle with the aligner.	Used for superimposition and measurement of cumulative tooth movement.

Figure 2. 3D-printed models showing varying degrees of central incisor malalignment alongside a thermoformed ClearX aligner

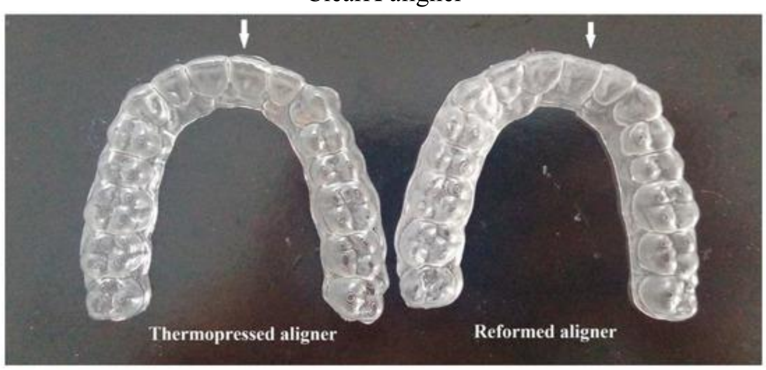

Figure 3. Thermo-pressed aligner on model 2 and reformed aligner adapted on model 1

Assessment of shape memory correction on the typodont model

The wax surrounding the upper left central incisor in Model T was first softened. Using the guiding splint, the tooth was repositioned to match the malalignment in Model 0. To stabilize the wax and prevent distortion during aligner placement, Model T was immersed in a 5 °C water bath for 10 minutes [7]. Once cooled, the model was scanned (Scan 1). The reformed aligner was then fitted onto Model T, and the assembly was submerged in a 50 °C water bath for 10 minutes. The water level was carefully adjusted to reach just below the aligner margin, preventing premature activation of the aligner's shape memory while allowing the wax to soften and permit tooth movement. After this step, the model was returned to a 5 °C water bath for 10 minutes to solidify the wax prior to aligner removal, followed by a scan (Scan 2).

To trigger shape memory recovery, the aligner underwent its first activation cycle using the ClearX Aligner Booster (v. 2.1, Kline-Europe GmbH, Düsseldorf, Germany), a programmable device controlled wirelessly via the ClearX Mobile App (v. 1.1.4) available for both Apple and Android devices. The device heats the aligner in water at a controlled temperature to restore its original shape. In this study, the aligner was submerged in 67 °C water within the device for 10 minutes. After activation, the aligner was fitted onto Model T and both were placed together in a 50 °C water bath for 10 minutes, maintaining the water level just below the aligner margin to avoid unintentional shape memory activation. The model was then scanned (Scan 3).

The aligner was subsequently subjected to a second activation cycle, followed by placement on Model T and immersion in the 50 °C water bath under the same conditions, after which the model was rescanned (Scan 4).

This entire procedure was repeated seven times using seven separate aligners (n = 7) to ensure reproducibility and consistency of the results. Fresh wax was used for each trial to prevent alterations in its properties due to repeated heating and cooling. Additionally, before each new aligner was applied, the initial malaligned position was rescanned (Scan 1) after repositioning the incisor with the guiding splint, minimizing potential measurement errors.

Figure 4. ClearX booster device operated via a mobile app to programmatically trigger shape memory activation in the ClearX aligners

Digital model evaluation

For each aligner, Model T was digitally scanned at four critical points throughout the procedure **(Figure 5)**: first, after the guiding splint was used to set the incisor in the full 1.9 mm malaligned position (Scan 1); second, following placement of the reformed aligner (Scan 2); third, after the aligner underwent its initial activation cycle (Scan 3); and fourth, after completion of the second activation cycle (Scan 4).

These scans were then aligned and overlaid using Ortho Analyzer software to calculate the linear movement of the incisor in millimeters. Measurements were recorded relative to the starting position (Scan 1) as well as relative to the immediately preceding step to evaluate incremental corrections **(Figure 6)**. A detailed summary of all models and scans used in the study is provided in **Table 1**, while **Figure 7** depicts a flowchart outlining the main steps of the ClearX aligner protocol.

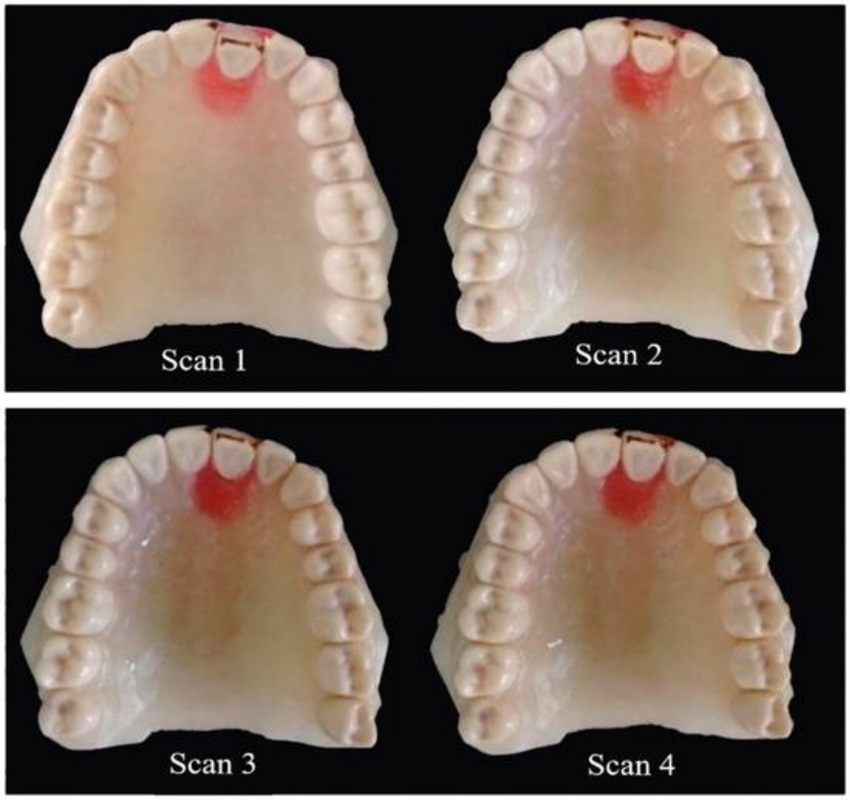

Figure 5. Model T shown prior to scanning at each stage of the treatment process

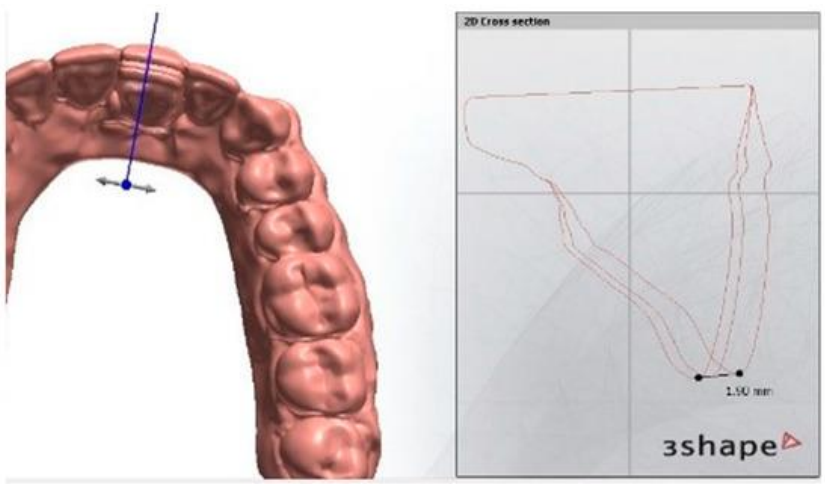

Figure 6. Superimposition of typodont scans using 3Shape Ortho Analyzer software to quantify tooth movement at each stage.

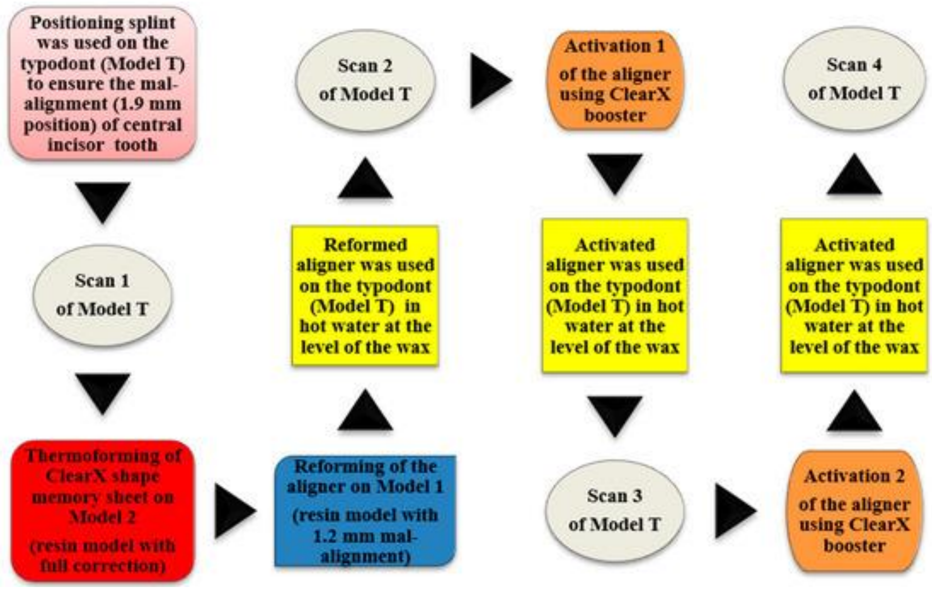

Figure 7. Flowchart depicting the key steps of the ClearX aligner protocol

Results

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

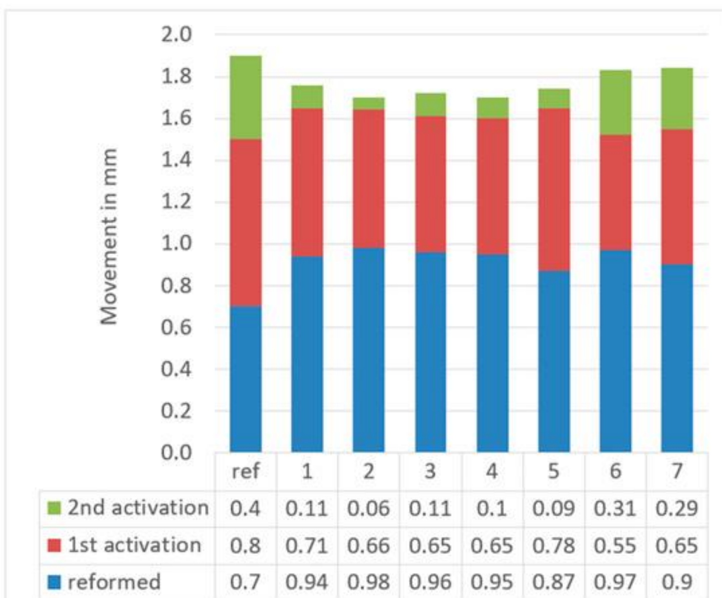

Figure 8. Stepwise corrective movement of the upper left central incisor on the typodont model achieved using seven ClearX aligners

Table 2. Average values and standard deviations (SD) for total cumulative correction (TC) of the upper left central incisor

position relative to the initial malaligned scan, the incremental correction (AC) determined by comparing each step's scan to the previous step, and the corresponding percentage of correction achieved by the ClearX aligner

	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%

Discussion

The primary goal of innovations and advancements in the field of orthodontic aligners is to simplify both fabrication and clinical procedures while minimizing treatment time and cost. One of the most significant developments in recent decades has been the integration of digital technology into aligner fabrication [1, 3]. Similarly, the introduction of novel materials for aligners has attracted considerable research interest [24-26]. Selecting an appropriate material is particularly challenging because it requires careful consideration of biocompatibility and biomechanical properties. Furthermore, developing a clinically feasible method to evaluate the shape memory characteristics of these materials presents additional complexity. Consequently, thorough in vitro investigations and material characterization are essential before clinical application.

In this study, smart polymers—specifically thermo-responsive shape memory polymers (SMPs)—were proposed for orthodontic aligner fabrication. These polymers can maintain two or more shapes and revert to their permanent configuration upon exposure to a suitable thermal stimulus or sequence of stimuli [27]. The ClearX system from Kline Europe GmbH, a thermo-responsive polyurethane-based thermoplastic sheet, was selected due to its claimed ability to regain its original thermoformed shape following a reforming step when thermally activated for a specified duration. The stepwise shape-changing capability of this material suggests that a single aligner could potentially replace multiple conventional aligners, thereby reducing the total number required per treatment. This approach could save both time and costs, particularly in complex cases such as molar distalization or severe open/deep bite corrections, which are increasingly common in contemporary orthodontics [28-30].

An additional advantage of the tested method is its compatibility with CAD/CAM systems, which are increasingly applied in dentistry, including restorative, prosthodontic, and orthodontic workflows. CAD/CAM technology enables a fully digital process from impression to final appliance fabrication, offering clinical reliability [31] and favorable patient feedback [32].

The present study demonstrated that approximately 92.63% of the total planned correction could be achieved on a typodont model through a single reforming step combined with two activation cycles, i.e., three procedural steps in total. The shape recovery performance of SMPs is influenced not only by their molecular structure and composition but also by processing parameters. Careful control of these factors is crucial for achieving predictable material behavior in practice [33]. Therefore, the study protocol was preceded by a series of sensitivity tests to optimize critical variables, including temperature, moisture, and duration at each stage. The thermoforming, reforming, and activation steps all exhibited high sensitivity to these parameters. Activation of the shape memory effect was conducted using the ClearX booster system **(Figure 4)**. Through sensitivity testing, optimal conditions were determined, with the first activation cycle producing an average of 65% of shape memory recovery and the second cycle contributing an additional 35%.

The underlying mechanism of the shape memory effect 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 [34]. In thermal-responsive SMPs, shape memory behavior arises from the reversible activation and immobilization of polymer chain segments above and below a specific transition temperature (T_{trans}), which may correspond to the glass transition temperature (T_g) or melting temperature (T_m) [14, 20, 35]. When the transition temperature is reached, the deformed material regains elasticity and returns to its original shape, generating forces capable of inducing tooth movement [36].

Thermo-responsive SMPs are capable of exhibiting more than one temporary configuration due to their broader shape recovery temperature range and higher recoverable strain [19, 27]. Shape memory polyurethane resins are composed of both polar and non-polar molecular segments that self-organize into microdomains of hard and soft regions. The integration of these domains allows the material to combine high strength (from the hard segments) with high toughness (from the soft segments), making it suitable for manufacturing durable orthodontic aligners capable of sustained tooth movement over extended periods [33, 37]. Moreover, polyurethane resins resist plaque and stain accumulation, maintaining cleanliness in the oral environment; however, they are sensitive to moisture because of hydrogen bonding [37-39], which likely explains the influence of moisture during the reforming and activation steps of ClearX aligners.

In theory, the reformed aligner is designed to produce a 0.7 mm corrective movement, with the first activation cycle contributing roughly 55–65% of the shape memory recovery, and the second activation adding 25–35%, depending on the magnitude and type of planned movement. In the present study, the reformed aligners produced an average movement of 0.94 mm, exceeding the planned 0.7 mm **(Table 2, Figure 8)**. This discrepancy may result from spontaneous recovery occurring during stress release or partial activation triggered by the 50 °C water bath used to soften the wax, leading to an additional 0.24 mm of movement, accounting for 20% of the total shape memory component.

Following the first activation, the aligners produced an additional 0.66 mm of movement, representing approximately 55% of the planned shape memory motion and yielding a cumulative movement of 1.6 mm (84.2% of the total 1.9 mm planned movement). The second activation added 0.15 mm, corresponding to 12.5% of the planned shape memory movement, resulting in an average total correction of 1.75 mm (92.63% of the planned movement). According to the ClearX system, the small remaining unrecovered portion (~7–8%) is intended to be completed with the subsequent "recurrent" aligner, which allows any delayed orthodontic adjustments to be addressed. Each new aligner is first used to verify full completion of the previous correction before activation to deliver further movement.

The consistent results across specimens indicate reliable material performance. Nevertheless, this study is limited to a proof-of-concept in vitro investigation on a typodont model. In this setup, wax simulates the periodontium, but true bone remodeling in response to orthodontic forces is a complex biological process involving intricate tissue biomechanics [40]. Additionally, only a single movable tooth was evaluated while all other teeth were immobilized in resin, which does not fully replicate clinical conditions. The influence of environmental factors, such as hot foods or beverages, which could prematurely activate the aligner in vivo, was not considered. Furthermore, the mechanical properties of the aligner and the forces generated by shape memory recovery need comprehensive investigation. These aspects will be addressed in future studies.

Conclusions

This study demonstrated that tooth movement can be achieved on a typodont model using clear aligners fabricated from shape memory polymers (SMPs). To activate their shape memory properties, the aligners must undergo a series of controlled heat treatments above their transition temperature. Therefore, SMP-based aligners hold potential as a promising option for future orthodontic treatments with an aesthetic focus.

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