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Force comparison between Perfitalign 4D aligners and thermoformed aligners for mandibular incisor retraction: an in vitro study

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Abstract

Objectives To quantitatively compare the orthodontic forces exerted during mandibular incisor retraction by Perfitalign 4D aligners and thermoformed aligners over a 60-hour dynamic monitoring period, assess tooth movement trends, and investigate the effects of shape-memory properties on force characteristics.

Materials and methods Three groups of aligners were designed for mandibular incisor retraction. Group A aligners were fabricated using Erkodur foils (ERKODENT Erich Kopp) via thermoforming, while Groups B and C were fabricated using DCA resin (LuxCreo) via 3D printing. Groups A and B possessed a step size of 0.15 mm, whereas group C had a step size of 0.20 mm. Force data were monitored on a mandibular model for 60 h using a multi-axis transducer at 4-hour wear intervals. Groups B and C underwent thermal reactivation after every 12 h of cumulative wear, with recordings taken immediately before and after each activation.

Results All groups exhibited high repeatability (ICC > 0.9). Perfitalign 4D aligners exhibited significant force recovery after thermal reactivation, though the recovery degree slightly decreased with repeated activations. Vertical forces markedly fluctuated but increased after thermal reactivation. Intergroup comparisons revealed significantly lower lingual forces in groups B/C compared to group A ($P < 0.05$). For mesiodistal and vertical directions, forces in groups B/C showed no significant reductions compared to group A. Residual stress analysis revealed rapid initial decay in group A, which decelerated subsequently, while groups B and C exhibited cyclic characteristics of "decay—thermal reactivation-induced recovery—decay". At 0 h, moment-to-force ratios (Mx/Fy) for mandibular incisors were significantly lower in groups B/C (− 3.3 to − 8.7 mm) than in group A (− 8.0 to − 10.7 mm).

Conclusion Perfitalign 4D aligners enable cyclic force recovery via shape-memory properties, independent of step size (0.15/0.20 mm). Despite larger steps, their lingual forces remained significantly lower than those of thermoformed aligners. A trend closer to bodily movement was observed with Perfitalign 4D aligners, although clinical studies are needed to validate movement efficiency and the long-term effects of elevated mesiodistal/vertical forces.

Keywords Clear aligners, 4D aligners, 3D-printed aligners, Retraction, Force

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Introduction

The clinical application of clear aligners dates back to 1945, when for the first time, Kesling et al. used tooth positioners made of elastic polymers without wires or brackets to treat minor malocclusions [1]. Although clear aligner therapy was initially indicated only for simple malocclusions, its indications subsequently expanded thanks to advances in material science and computer-aided design/computer-aided manufacturing (CAD/CAM). Growing clinical adoption has fueled in-depth research, prompting continuous innovations in aligner materials and fabrication techniques.

Conventional clear aligners are primarily fabricated from thermoplastic polymeric foils, including thermoplastic polyurethane (TPU), polyethylene terephthalate glycol (PETG), polyethylene terephthalate (PET), polypropylene (PP), ethylene-vinyl acetate (EVA), and polycarbonate (PC) [2–4]. To leverage the advantages of different materials, manufacturers have developed multilayer laminates. For instance, Invisalign's SmartTrack™ (LD30) combines TPU and copolyester layers, offering enhanced elongation and stable mechanical properties [5].

Despite significant advancements in material development and optimization of existing materials, thermoformed aligners still suffer from inherent limitations. Current commercial aligners exhibit elevated initial stress. Several in vitro studies confirmed that the initial forces exerted by clear aligners substantially exceed recommended levels [6–8], potentially increasing the risk of periodontal damage, particularly among patients with reduced alveolar bone height. Moreover, the thermoforming process involves intricate procedures that adversely affect key mechanical properties of aligners, including elastic modulus, hardness, transparency, and water absorption [9–11], and lead to irregular thicknes s [12, 13]. As aligner thickness critically affects force magnitude [14], these inconsistencies make clinically delivered forces less predictable.

The concept of 4D printing was first proposed by Tibbits from MIT at the 2013 TED Conference in the US [15]. Its central concept lies in utilizing the stimulus-responsive properties of programmable materials to construct dynamic structures via 3D printing. These structures can autonomously alter their morphology, properties, or functions in the presence of external stimuli (shape memory characteristics). To overcome the inherent limitations of the thermoformed aligners, several companies have developed 4D-printed materials. The photocurable polyurethane Tera Harz TC-85 from Graphy (approved by Korean MFDS, EU EC, and US FDA [1]) and the transparent photopolymer resin DCA from LuxCreo (granted China NMPA Class II Medical Device Certification and US FDA 510(k) clearance [16]) are the currently authorized materials. Perfitalign is a type of 4D aligner fabricated from DCA resin.

Compared to thermoformed aligners, 4D aligners demonstrate distinct advantages but also face limitations that require resolution [17]. These potential advantages are evidenced in several aspects. First, shape-memory properties significantly minimize force attenuation, attenuating pronounced decay in thermoformed aligners caused by both polymer viscoelasticity and insertion/removal-induced plastic deformation [18]. Second, direct 3D printing resolves the need for sequential models and post-thermoforming trimming, streamlining production while reducing costs and manufacturing waste [19]. It also prevents error accumulation during dental model fabrication and thermoforming [20]. In the study conducted by Lee et al. [1], thermoformed aligners retained only 54.7% of their pre-thermoforming thickness, while 3D-printed aligners showed merely 12% deviation from design thickness, offering significantly lower thickness variability. Studies by Jindal and Koenig et al. [14, 21] also confirmed enhanced precision in 3D-printed aligners. Additionally, region-specific thickness customization can be implemented based on the categories of tooth movement, improving the accuracy of targeted tooth displacement and reducing the risk of side effects, thereby improving clinical predictability [22]. The primary challenges for 4D aligners are related to biocompatibility and long-term performance. Previous reports regarding their biosafety remain inconsistent. In studies involving TC-85 and TA-28 (also a 4D aligner material from Graphy) resins, some reports mentioned no cytotoxic effects, while others identified mild toxicity or toxicity associated with post-curing parameters. The significant experimental heterogeneity among studies makes it difficult to draw definitive conclusions [23–25]. Furthermore, its greater increase in surface roughness compared to thermoformed aligners after intraoral use may facilitate bacterial adhesion and biofilm formation [26]. Therefore, while acknowledging the advantages of 4D aligners, it is essential to prioritize standardized biosafety verification, optimize post-processing procedures, and evaluate their long-term clinical performance.

The shape-memory properties of 4D aligners result in fundamentally distinct force-related behavior compared to thermoformed aligners. Current research on Tera Harz TC-85 is relatively comprehensive. Through static mechanical testing and dynamic mechanical analysis, Lee et al. [1] investigated its viscoelastic properties, mechanical responses, and shape-memory characteristics under thermal variations. Atta et al. [27] quantified critical physical and mechanical parameters of the material, including glass transition temperature, storage modulus, flexural strength, and hardness. Can et al. [28] retrieved Tera Harz TC-85 aligners from patients to investigate the effects of aging on mechanical performance. Other studies employed transducers to measure forces and moments generated by these aligners during various orthodontic movements [21, 29, 30]. Attention has also been paid to Tera Harz TA-28 of the same series. Using transducer measurements, one study reported distinct force patterns of TA-28 aligners during labial inclination of the upper right lateral incisor compared to thermoformed aligners [31].

However, research on Perfitalign 4D aligners remains limited. Divergent stimulus-responsive properties of 4D materials may lead to substantially different force characteristics, rendering existing conclusions inapplicable to Perfitalign 4D aligners. Differing from static studies measuring only initial forces, this study conducted dynamic measurements at 16 time points over 60 h to quantify short-term dynamic changes in three-dimensional force during mandibular incisor retraction with Perfitalign 4D and thermoformed aligners. We also explored shape-memory effects on orthodontic force. Additionally, moment-to-force ratios in primary force directions were analyzed to compare incisor displacement patterns induced by both aligner types.

Materials and methods

Construction of the test apparatus

This study enrolled a 28-year-old male volunteer with a complete mandibular dentition exhibiting neat alignment. Intraoral scans and cone-beam computed tomography (CBCT) data of the participant were acquired. The experimental protocol was approved by the Ethics Committee of the Third Hospital Affiliated of Air Force Military Medical University (Approval No. KQ-YJ-2025-197). The study strictly adhered to the principles of the Declaration of Helsinki for research on human subjects.

The 3D models of individual teeth were segmented using Linkedsmile Shaper software (Linkedsmile Medical Technology Co., Ltd., Wuxi, China). Crown fixtures and experimental platforms were designed in SolidWorks 2012 (Dassault Systèmes, Paris, France). After refinement in Geomagic Wrap 2021 (3D Systems, Rock Hill, SC, USA), components were assembled with dental models, maintaining 0.5 mm interproximal clearance. Industrial stereolithography apparatus (SLA) systems (Lite300, UnionTech, Shanghai, China) were used to produce the 3D models. Crown-fixture assemblies were integrated with NANO17-E transducers (ATI Industrial Automation, Apex, NC, USA) and testing platforms via retention screws (Fig. 1a). The data acquisition system connected the transducer, signal conditioner, data acquisition card, and computer in a series manner (Fig. 1b). Force/torque data were recorded in a real-time manner using ft_reader software (Linkedsmile Medical Technology Co., Ltd., Wuxi, China) and saved as Excel files (Fig. 1c).

Dental model and aligner fabrication

STL data of the dentition for the transducer system was acquired using an intraoral scanner (TRIOS, 3Shape, Copenhagen, Denmark). Based on these data, 15 identical dental models were fabricated using photocurable resin UTR 3500 (Prismlab, Shanghai, China) and an industrial SLA printer (Lite300, UnionTech, Wuxi, China). This quantity corresponds to the number of aligners used for force measurement. In the intervals between measurements, each aligner was seated on a model to sustain a continuous load, simulating the clinical stress relaxation process. Master models for thermoformed aligner production were also printed using the same system.

In total, 18 aligners (6 per group; 1 for repeatability testing and 5 for consistency checks and force measurements) and 8 retainers (4 Erkodur and 4 Perfitalign 4D) were fabricated according to the following production workflow. Based on the STL dataset, aligner digital designs were completed using Linkedsmile Treat software (Linkedsmile Medical Technology Co., Ltd., Wuxi, China). A 0.15 mm mandibular incisor retraction was preset for group A (Fig. 2a). These aligners were fabricated from 0.80 mm-thick Erkodur foils (ERKODENT Erich Kopp, Pfalzgrafenweiler, Germany) using Ministar S thermoforming equipment (Scheu-Dental GmbH,

Fig. 1 The force measurement system. **a** 3D-printed resin crown integrated with a multi-axis force/torque transducer via retention screws, **b** Transducer platform and signal conditioner, **c** Computer running ft_reader software with real-time monitoring interface, connected to the force measurement system

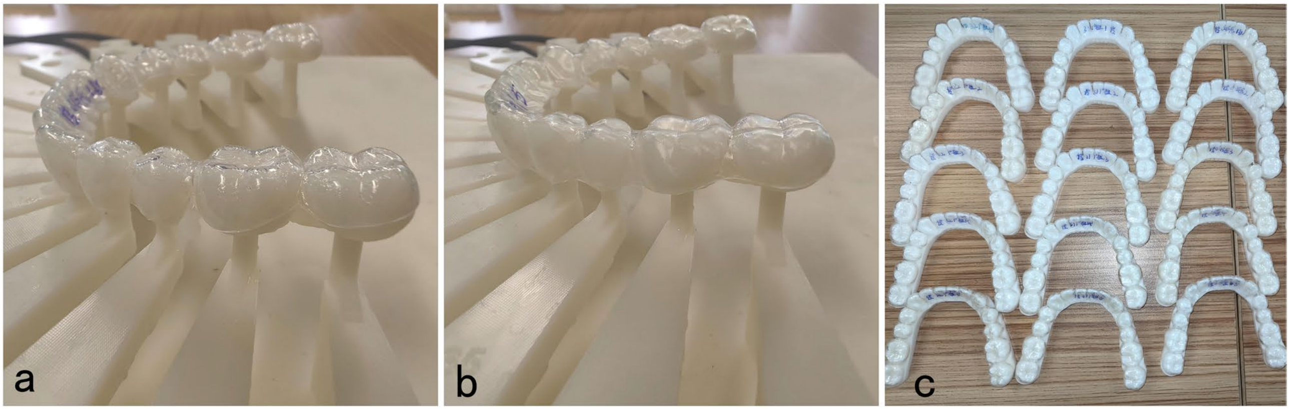

Fig. 2 Experimental setup and compared aligner types. **a** Thermoformed aligner mounted on the force transducer. **b** Perfitalign 4D aligner mounted on the force transducer. **c** Aligners on resin dentoform models for long-term wear simulation

Iserlohn, Germany) following the manufacturer's instructions. After cooling, the clear aligners were separated from the models and trimmed with a scalloped margin along the gingival edge. DCA photocurable resin (LuxCreo, Beijing, China) was used for groups B and C, and all production steps were conducted strictly following the manufacturer's specifications. Mandibular incisor retraction was preset at 0.15 mm (Group B) and 0.20 mm (Group C), respectively (Fig. 2b). The aligner design data were imported into LuxDesign software (LuxCreo, Beijing, China) to generate 0.6 mm-thick digital aligners. They were printed using an industrial DLP 3D printer (iLux ProDental, LuxCreo, Beijing, China) with key parameters, including 100 μm layer thickness and 45° build orientation, set following the manufacturer's recommendations. After printing, the aligners underwent standard post-processing: isopropanol cleaning (12 min), UV light curing (385–405 nm, 30 min), thermal drying (130 °C), and polishing.

Data collection

The coordinates of the centers of resistance (CRs) were determined using MeshLab software (Visual Computing Lab, ISTI-CNR, Italy) and input into the data acquisition software to transform the forces and moments output by the transducer to the CR of each tooth. A local coordinate system was defined for each tooth wherein the x-axis aligned with the mesiodistal direction (positive Fx: distal force; positive Mx: crown lingual tipping), the y-axis corresponded to the labiolingual/buccolingual direction (positive Fy: labial/buccal force), and the z-axis paralleled the long axis of each tooth (positive Fz: extrusive force).

Before testing, a uniform layer of petroleum jelly was applied to the crown surfaces to simulate the humid environment of the oral cavity. After full seating of the clear aligner, data were acquired at 1 Hz for 3 min. A segment of 10 consecutive data points with minimal fluctuation was selected and averaged. The total measurement duration was 60 h, and data was collected every 4 h of wear. In the intervals between measurements, the clear aligner was inserted into the resin dental model (Fig. 2c). It should be noted that Perfitalign 4D aligners were fabricated from DCA photocurable resin (LuxCreo, Beijing, China), a material with a high transition temperature (60 °C). In clinical practice, the manufacturer recommends that patients soak the aligner in hot water above 65 °C for 15 min every 12 h to activate the shape memory effect and restore the aligner force. To accurately simulate this essential clinical procedure, a thermal reactivation treatment (immersion in hot water above 65 °C for 15 min) was conducted for Groups B and C every 12 h of wear, and data were collected before and after reactivation. The net forces and moments were obtained by subtracting retainer baseline values from aligner measurements. The mean of five aligners was reported as the final result of each group. To mitigate the effect of repeated insertion/removal or manufacturing deviations on force, one randomly selected aligner in each group (A1, B1, C1) was subjected to 15 cycles of insertion and removal for repeatability testing. Intra-group consistency was verified using 0-hour measurements. All procedures were conducted by the same operator using the same set of instruments.

Statistical analysis

Statistical analysis was conducted using SPSS 25.0 software (IBM Co., Armonk, NY, USA). Intraclass correlation coefficient (ICC, 95% CI) was employed to evaluate repeatability across 15 insertion/removal cycles and intra-group consistency of 0-hour measurements. The orthodontic forces on mandibular incisors for groups A, B, and C are presented as mean ± standard deviation after 0, 4, 12, 24, 36, 48, and 60 h of wear. The percentage of residual stress (PRS) was calculated using the following formula: PRS = $(\sigma_t/\sigma_0) \times 100\%$, where σ_t represents the mean force at time t and σ_0 denotes the initial force

Table 1 Repeatability testing of differently designed aligners after 15 insertion/removal cycles

Group	A1			B1			C1		
Dir. F	Fx	Fy	Fz	Fx	Fy	Fz	Fx	Fy	Fz
ICC	0.981	0.992	0.990	0.950	0.990	0.989	0.961	0.968	0.992
95%CI	0.962–0.993	0.984–0.997	0.980–0.996	0.901–0.981	0.980–0.996	0.977–0.996	0.923–0.985	0.937–0.988	0.985–0.997

Table 2 Verification of the intra-specimen consistency of identically designed aligners

Group	A			B			C		
Dir. F	Fx	Fy	Fz	Fx	Fy	Fz	Fx	Fy	Fz
ICC	0.989	0.986	0.918	0.989	0.974	0.930	0.989	0.966	0.945
95%CI	0.977–0.996	0.969–0.995	0.822–0.970	0.976–0.996	0.943–0.990	0.848–0.974	0.977–0.996	0.926–0.987	0.881–0.980

(at 0 h). Data from 0, 4, 12, 24, and 60 h were subjected to pairwise inter-group comparisons using the Mann-Whitney U test ($\alpha = 0.05$), with only post-activation data included in the analysis for groups B and C due to their significantly lower force magnitude before thermal activation. Given the low magnitude of vertical forces (Fz) and their increased susceptibility to measurement error, the analysis of force trends over the 60-hour period was confined exclusively to the changes in mesiodistal (Fx) and labiolingual (Fy) forces. Additionally, the Mx/Fy ratio at 0 h was computed for mandibular incisors to evaluate the tooth movement trend.

Results

Repeatability and inter-specimen consistency

Fifteen repeated insertion/removal measurements on aligners A1, B1, and C1 (Table 1) confirmed excellent repeatability under operational cycling, with ICC more than 0.90 (range: 0.950 ~ 0.992) across all force axes. Inter-specimen consistency verification for five aligners per group at 0 h (Table 2) indicated high manufacturing precision, as ICC values for Fx, Fy, and Fz all surpassed 0.90, suggesting that they passed the consistency test.

Dir. F stands for directional force; ICC stands for intraclass correlation coefficient; 95% CI stands for 95% confidence interval. The definitions of each group and the description of force directions can be found in the “Materials and Methods” section. The force measurement results are provided in Table S1.

The force measurement results are provided in Table S2. Abbreviations follow Table 1.

The effects of shape memory properties on force-related behavior of perfitalign 4D aligners

Force magnitudes and PRS for Perfitalign 4D aligners before and after thermal reactivation are detailed in Tables 3 and 4. Reactivation significantly modulated force-related behavior. Before the initial reactivation (at 12 h), mesiodistal forces in groups B and C decreased to an average of 47.05% (range: 37.25 ~ 54.28%) and 44.01% (31.39 ~ 53.35%) of baseline values, respectively, and recovered to 74.81% (73.06 ~ 76.76%) and 70.36% (61.43 ~ 77.63%) after reactivation. At the 24-hour timepoint before the second reactivation, mesiodistal forces further decreased to an average of 31.87% (group B: 20.57 ~ 37.88%) and 31.06% (group C: 22.11 ~ 35.01%) of baseline. After the second reactivation, recovery percentages were slightly reduced compared to those after the first reactivation (group B: 65.49%; group C: 69.07%). Throughout the experimental period, recovery efficiency of mesiodistal forces exhibited a gradual decline with increasing reactivation cycles. Nevertheless, after 60 h of wear, the force could still recover to an average of 58.44% and 63.18% of its initial values, respectively.

Labiolingual force variations followed patterns similar to those of mesiodistal forces. Before the first thermal reactivation, labiolingual forces in groups B and C decreased to an average of 45.51% (33.83 ~ 53.57%) and 45.26% (37.77 ~ 55.37%) of baseline values, and recovered to 65.03% (58.60 ~ 74.43%) and 62.86% (57.81 ~ 69.89%) after reactivation, respectively. After 60 h of wear, they could still recover to an average of 58.20% and 56.69% of the initial values, respectively. Vertical forces exhibited considerably lower magnitudes, where minor absolute fluctuations yielded disproportionately large percentage variations. Therefore, certain incisors exhibited divergent trends compared to the pattern of mesiodistal/labiolingual forces, although overall vertical values increased after reactivation. Figure 3 illustrates force changes in mesiodistal and labiolingual directions for Perfitalign 4D aligners before and after the second thermal reactivation.

Intergroup differences in static forces

Orthodontic forces at 0, 4, 12, 24, and 60 h were compared between groups (Table 5), with magnitudes detailed in Table 3. Group A indicated significantly greater lingual forces on mandibular incisors than groups B and C. Left incisors were subjected to mesial forces, while right incisors received distal forces. Except for the left central incisor under light intrusive force, all teeth were subjected to extrusive forces. The three-dimensional force directions on the incisors in group B were generally consistent with those in group (A) However, lingual forces were significantly reduced in group (B) Except for

Table 3 Forces on mandibular incisors at various time points during 60 h wear

Time		0 h			4 h			12 h	
Dir. F(N)	Tooth	A	B	C	A	B	C	A	B
Fx	32	−0.592±0.062	−0.423±0.161	−0.675±0.102	−0.536±0.082	−0.124±0.105	−0.448±0.072	−0.392±0.085	−0.157±0.055
	31	−0.408±0.056	−0.671±0.085	−0.678±0.071	−0.301±0.030	−0.411±0.071	−0.411±0.101	−0.320±0.064	−0.364±0.086
	41	0.353±0.068	0.622±0.082	0.541±0.054	0.319±0.009	0.318±0.088	0.281±0.064	0.263±0.004	0.284±0.032
	42	0.604±0.097	0.410±0.070	0.709±0.109	0.524±0.076	0.288±0.056	0.469±0.043	0.458±0.056	0.209±0.046
Fy	32	−1.314±0.067	−0.796±0.093	−1.069±0.09	−1.070±0.185	−0.310±0.057	−0.740±0.048	−0.928±0.113	−0.269±0.12
	31	−1.190±0.071	−0.770±0.070	−0.859±0.086	−0.821±0.205	−0.461±0.109	−0.595±0.032	−0.893±0.203	−0.412±0.030
	41	−1.397±0.069	−0.811±0.092	−1.093±0.091	−1.161±0.200	−0.405±0.109	−0.511±0.056	−1.028±0.145	−0.335±0.073
	42	−1.523±0.085	−0.903±0.062	−1.124±0.087	−1.310±0.111	−0.632±0.115	−0.697±0.104	−1.167±0.106	−0.481±0.092
Fz	32	0.115±0.044	0.297±0.097	0.374±0.106	0.105±0.055	0.191±0.051	0.279±0.057	0.086±0.024	0.174±0.078
	31	−0.032±0.062	0.045±0.063	0.029±0.016	−0.025±0.053	0.073±0.064	0.061±0.038	−0.017±0.052	0.100±0.013
	41	0.127±0.160	0.215±0.088	0.280±0.052	0.109±0.102	0.102±0.027	0.086±0.026	0.110±0.05	0.077±0.028

Time		12 h			24 h				
Dir. F(N)	Tooth	C	B‡	C‡	A	B	C	B‡	C‡
Fx	32	−0.212±0.076	−0.324±0.113	−0.469±0.118	−0.412±0.070	−0.087±0.044	−0.149±0.052	−0.287±0.092	−0.506±0.136
	31	−0.312±0.116	−0.491±0.040	−0.495±0.095	−0.269±0.051	−0.254±0.070	−0.238±0.061	−0.459±0.065	−0.490±0.096
	41	0.245±0.049	0.475±0.140	0.420±0.061	0.292±0.025	0.211±0.057	0.186±0.045	0.415±0.101	0.384±0.032
	42	0.378±0.050	0.300±0.123	0.436±0.117	0.449±0.063	0.144±0.043	0.232±0.035	0.242±0.130	0.412±0.138
Fy	32	−0.404±0.140	−0.517±0.166	−0.705±0.139	−0.926±0.100	−0.147±0.041	−0.300±0.070	−0.440±0.119	−0.674±0.148
	31	−0.476±0.119	−0.573±0.102	−0.601±0.055	−0.780±0.163	−0.273±0.045	−0.321±0.036	−0.530±0.089	−0.542±0.099
	41	−0.415±0.087	−0.504±0.166	−0.632±0.102	−1.027±0.213	−0.208±0.111	−0.224±0.058	−0.453±0.174	−0.545±0.096
	42	−0.561±0.188	−0.529±0.202	−0.650±0.140	−1.083±0.089	−0.313±0.108	−0.356±0.118	−0.526±0.170	−0.623±0.170
Fz	32	0.193±0.034	0.193±0.077	0.313±0.072	0.098±0.043	0.123±0.047	0.160±0.045	0.198±0.055	0.252±0.048
	31	0.076±0.039	0.055±0.049	−0.006±0.046	−0.037±0.066	0.057±0.031	0.044±0.028	0.053±0.014	−0.018±0.037
	41	0.055±0.016	0.128±0.067	0.135±0.050	0.040±0.032	0.052±0.016	0.034±0.009	0.130±0.055	0.134±0.080
	42	0.186±0.027	0.362±0.099	0.253±0.095	0.206±0.051	0.188±0.030	0.153±0.032	0.355±0.063	0.247±0.054

Time		36 h					48 h		
Dir. F(N)	Tooth	A	B	C	B‡	C‡	A	B	C
Fx	32	−0.411±0.069	−0.065±0.035	−0.151±0.045	−0.247±0.123	−0.419±0.105	−0.305±0.053	−0.081±0.063	−0.143±0.067
	31	−0.268±0.061	−0.232±0.053	−0.206±0.055	−0.426±0.077	−0.476±0.085	−0.219±0.046	−0.241±0.046	−0.234±0.053
	41	0.256±0.015	0.227±0.075	0.196±0.024	0.424±0.110	0.455±0.042	0.220±0.049	0.217±0.089	0.206±0.056
	42	0.439±0.060	0.127±0.022	0.203±0.054	0.253±0.080	0.399±0.136	0.373±0.114	0.139±0.032	0.223±0.036
Fy	32	−0.886±0.095	−0.105±0.042	−0.246±0.074	−0.455±0.191	−0.706±0.139	−0.855±0.101	−0.176±0.083	−0.310±0.086
	31	−0.661±0.126	−0.269±0.030	−0.302±0.088	−0.514±0.061	−0.565±0.089	−0.636±0.114	−0.305±0.051	−0.380±0.094
	41	−0.926±0.218	−0.235±0.087	−0.210±0.081	−0.435±0.201	−0.530±0.073	−0.849±0.139	−0.232±0.118	−0.267±0.100
	42	−1.092±0.102	−0.306±0.062	−0.329±0.076	−0.507±0.188	−0.635±0.139	−1.014±0.117	−0.292±0.061	−0.363±0.086
Fz	32	0.071±0.042	0.131±0.024	0.157±0.035	0.201±0.089	0.274±0.026	0.092±0.041	0.145±0.048	0.160±0.063
	31	−0.067±0.032	0.042±0.026	0.070±0.031	0.032±0.083	−0.023±0.040	−0.055±0.023	0.053±0.037	0.059±0.032
	41	0.093±0.040	0.053±0.020	0.040±0.029	0.097±0.071	0.111±0.045	0.091±0.037	0.055±0.028	0.022±0.012

Time		48 h		60 h				
Dir. F(N)	Tooth	B‡	C‡	A	B	C	B‡	C‡
Fx	32	−0.257±0.066	−0.431±0.098	−0.209±0.052	−0.086±0.058	−0.157±0.052	−0.244±0.063	−0.405±0.093
	31	−0.429±0.028	−0.455±0.086	−0.176±0.042	−0.202±0.056	−0.159±0.062	−0.407±0.027	−0.431±0.076
	41	0.411±0.064	0.415±0.043	0.174±0.015	0.214±0.090	0.168±0.032	0.375±0.031	0.402±0.106
	42	0.242±0.061	0.404±0.129	0.409±0.044	0.109±0.048	0.122±0.023	0.226±0.058	0.390±0.108
Fy	32	−0.503±0.150	−0.701±0.146	−0.694±0.119	−0.126±0.034	−0.278±0.070	−0.500±0.126	−0.698±0.169
	31	−0.538±0.123	−0.520±0.096	−0.555±0.088	−0.239±0.045	−0.264±0.066	−0.512±0.117	−0.494±0.093
	41	−0.446±0.140	−0.512±0.090	−0.752±0.176	−0.245±0.108	−0.147±0.063	−0.420±0.132	−0.568±0.090
	42	−0.490±0.104	−0.616±0.097	−0.971±0.141	−0.255±0.099	−0.219±0.097	−0.468±0.124	−0.584±0.079
Fz	32	0.170±0.048	0.279±0.050	0.088±0.037	0.082±0.035	0.139±0.025	0.119±0.046	0.233±0.065
	31	0.042±0.013	0.031±0.025	−0.011±0.022	0.055±0.033	0.070±0.012	0.039±0.012	0.028±0.024
	41	0.092±0.013	0.117±0.031	0.086±0.030	0.056±0.036	0.016±0.018	0.088±0.012	0.103±0.031
	42	0.324±0.066	0.229±0.049	0.099±0.028	0.156±0.060	0.108±0.043	0.301±0.053	0.163±0.048

‡Indicates after reactivation, tooth numbers follow FDI notation, and values are presented as mean ± standard deviation. Dir. F stands for directional force

Table 4 Percentage of residual stress (%) over 60 h

Time		4 h			8 h			12 h					16 h		
Dir. F	**Tooth**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**B‡**	**C‡**	**A**	**B**	**C**
Fx	32	90.50	29.35	66.34	80.23	25.10	37.21	66.26	37.25	31.39	76.76	69.44	69.47	32.03	34.32
	31	73.74	61.19	60.55	70.92	58.09	51.00	78.32	54.28	46.06	73.13	72.93	63.98	43.92	44.94
	41	90.34	51.02	51.96	82.70	48.53	47.03	74.49	45.67	45.25	76.28	77.63	79.77	39.71	46.16
	42	86.72	70.21	66.11	72.72	58.76	57.00	75.71	50.99	53.35	73.06	61.43	67.50	41.43	36.19
	Mean	85.33	52.94	61.24	76.64	47.62	48.06	73.69	47.05	44.01	74.81	70.36	70.18	39.27	40.40
Fy	32	81.46	38.91	69.26	76.81	31.19	41.02	70.64	33.83	37.77	64.99	65.92	73.91	28.74	37.00
	31	69.00	59.93	69.21	67.68	57.45	51.03	75.08	53.57	55.37	74.43	69.89	64.78	45.81	49.73
	41	83.08	49.96	46.78	76.73	46.41	41.01	73.54	41.35	37.95	62.12	57.81	73.73	33.99	35.91
	42	85.99	69.99	61.97	79.92	59.28	51.02	76.63	53.29	49.93	58.60	57.81	77.16	41.19	36.17
	Mean	79.88	54.70	61.80	75.28	48.58	46.02	73.97	45.51	45.26	65.03	62.86	72.40	37.43	39.70
Fz	32	90.83	64.17	74.53	83.67	75.72	60.77	74.63	58.50	51.57	64.87	83.68	42.32	54.22	68.93
	31	76.76	164.82	182.49	67.42	191.20	103.72	51.21	225.03	262.34	123.99	− 21.08	44.31	151.07	295.66
	41	86.34	47.53	30.80	80.12	38.88	20.93	86.90	36.01	19.81	59.66	48.31	83.27	39.69	24.43
	42	77.58	61.49	61.67	61.76	56.76	49.49	65.82	41.77	48.80	68.01	66.19	56.17	42.60	56.38
Time		**20 h**			**24 h**					**28 h**			**32 h**		
Dir. F	**Tooth**	**A**	**B**	**C**	**A**	**B**	**C**	**B‡**	**C‡**	**A**	**B**	**C**	**A**	**B**	**C**
Fx	32	65.74	23.40	28.85	69.69	20.57	22.11	67.99	74.96	67.43	19.96	38.90	66.59	18.26	25.84
	31	63.17	38.10	39.87	65.83	37.88	35.01	68.42	72.30	60.60	41.35	39.01	63.72	38.44	34.88
	41	75.88	35.66	35.19	82.65	33.82	34.42	66.70	70.92	72.88	35.65	45.02	72.82	34.22	38.21
	42	70.03	36.72	34.96	74.29	35.20	32.69	58.86	58.11	68.08	37.79	30.92	69.76	30.45	30.09
	Mean	68.70	33.47	34.72	73.11	31.87	31.06	65.49	69.07	67.25	33.69	38.46	68.22	30.34	32.26
Fy	32	72.54	25.84	32.34	70.50	18.47	28.11	55.29	63.01	70.02	17.52	32.96	68.20	15.18	27.20
	31	62.65	41.34	42.78	65.55	35.46	37.32	68.82	63.11	61.65	37.72	43.27	47.20	37.38	39.57
	41	70.27	29.82	23.47	73.47	25.68	20.47	55.83	49.85	70.75	40.20	27.16	68.76	32.44	21.01
	42	73.63	38.43	33.39	71.10	34.64	31.64	58.17	55.41	73.85	36.03	34.67	72.81	35.47	30.56
	Mean	69.77	33.86	33.00	70.16	28.56	29.38	59.53	57.84	69.07	32.87	34.52	64.24	30.12	29.59
Fz	32	83.74	47.80	68.78	84.82	41.53	42.76	66.66	67.35	69.53	59.61	46.63	73.83	51.18	38.11
	31	63.79	111.66	182.62	113.17	128.18	151.33	118.46	− 63.63	163.54	116.96	186.25	138.25	110.53	188.55
	41	77.41	28.11	13.56	31.95	24.00	12.05	60.49	48.02	86.77	50.29	22.42	68.99	29.56	9.65
	42	59.85	35.19	44.38	69.11	35.27	40.04	66.70	64.60	61.40	32.88	46.52	59.85	31.19	42.93
Time		**36 h**					**40 h**			**44 h**			**48 h**		
Dir. F	**Tooth**	**A**	**B**	**C**	**B‡**	**C‡**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Fx	32	69.44	15.27	22.42	58.45	62.04	66.41	35.07	28.87	65.35	22.50	23.00	51.48	19.06	21.24
	31	65.69	34.59	30.41	63.54	70.21	63.76	36.12	35.59	60.72	35.75	35.10	53.53	35.95	34.47
	41	72.51	36.53	36.18	68.10	84.10	69.39	37.24	42.49	65.82	36.64	37.61	62.37	34.91	38.10
	42	72.56	31.04	28.62	61.55	56.31	70.66	37.97	37.62	70.64	32.91	35.48	61.69	33.88	31.40
	Mean	70.05	29.36	29.41	62.91	68.16	67.56	36.60	36.14	65.63	31.95	32.80	57.27	30.95	31.30
Fy	32	67.44	13.25	23.05	57.24	66.00	62.91	34.55	39.48	65.52	25.96	32.98	65.05	22.13	29.03

Table 4 (continued)

Time		36 h					40 h			44 h			48 h		
Dir. F	**Tooth**	**A**	**B**	**C**	**B‡**	**C‡**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
	31	55.58	34.93	35.17	66.77	65.75	54.49	42.09	53.98	57.81	44.90	45.33	53.44	39.57	44.28
	41	66.29	28.93	19.23	53.63	48.48	65.55	31.85	35.96	68.03	30.52	26.15	60.79	28.54	24.39
	42	71.70	33.84	29.30	56.11	56.48	70.43	37.27	37.81	72.92	33.41	34.56	66.57	32.37	32.31
	Mean	65.25	27.74	26.69	58.44	59.18	63.35	36.44	41.81	66.07	33.70	34.76	61.46	30.65	32.50
Fz	32	61.16	44.23	41.99	67.74	73.24	64.85	66.84	53.49	64.28	51.96	47.89	79.72	48.84	42.87
	31	205.40	93.30	240.53	71.72	-79.12	179.32	106.39	169.07	181.83	105.15	220.88	169.84	118.23	202.88
	41	73.67	24.53	14.45	45.32	39.84	71.65	29.83	26.75	89.01	30.07	18.67	71.56	25.44	7.80
	42	60.73	30.33	27.88	62.60	64.04	60.46	47.09	45.16	58.69	37.30	43.30	45.49	35.60	32.48

Time		48 h		52 h			56 h			60 h					
Dir. F	**Tooth**	**B‡**	**C‡**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**B‡**	**C‡**	
Fx	32	60.72	63.86	50.35	26.79	31.04	48.20	28.80	23.72	35.27	20.32	23.31	57.85	60.04	
	31	63.92	67.10	51.45	36.39	37.64	44.97	38.53	28.57	43.17	30.06	23.39	60.60	63.48	
	41	66.04	76.71	60.17	35.91	37.41	46.49	36.59	33.43	49.26	34.43	31.10	60.32	74.22	
	42	58.95	57.01	65.81	36.34	36.74	73.92	34.55	27.45	67.66	26.69	17.14	54.98	55.00	
	Mean	62.41	66.17	56.95	33.86	35.71	53.40	34.62	28.29	48.84	27.87	23.73	58.44	63.18	
Fy	32	63.18	65.53	64.44	28.74	43.10	59.66	22.70	32.11	52.80	15.86	26.00	62.82	65.29	
	31	69.86	60.51	51.62	42.36	41.18	50.36	38.66	37.97	46.64	31.10	30.74	66.48	57.54	
	41	54.96	46.88	59.64	35.88	28.91	57.10	30.90	19.46	53.82	30.17	13.41	51.71	51.98	
	42	54.22	54.78	69.23	39.85	32.01	68.68	38.22	27.04	63.76	28.25	19.45	51.80	51.97	
	Mean	60.55	56.93	61.23	36.71	36.30	58.95	32.62	29.15	54.25	26.34	22.40	58.20	56.69	
Fz	32	57.07	74.62	83.65	39.29	52.74	76.14	34.68	38.77	76.35	27.65	37.14	40.14	62.38	
	31	93.79	105.37	156.10	62.15	187.95	222.01	119.48	203.30	32.67	123.31	240.97	87.51	97.61	
	41	42.97	41.78	72.95	20.34	7.77	71.22	27.96	10.66	67.52	25.99	5.83	40.89	36.95	
	42	60.88	60.04	50.44	39.76	49.94	42.66	38.76	49.26	33.07	29.27	28.16	56.52	42.69	

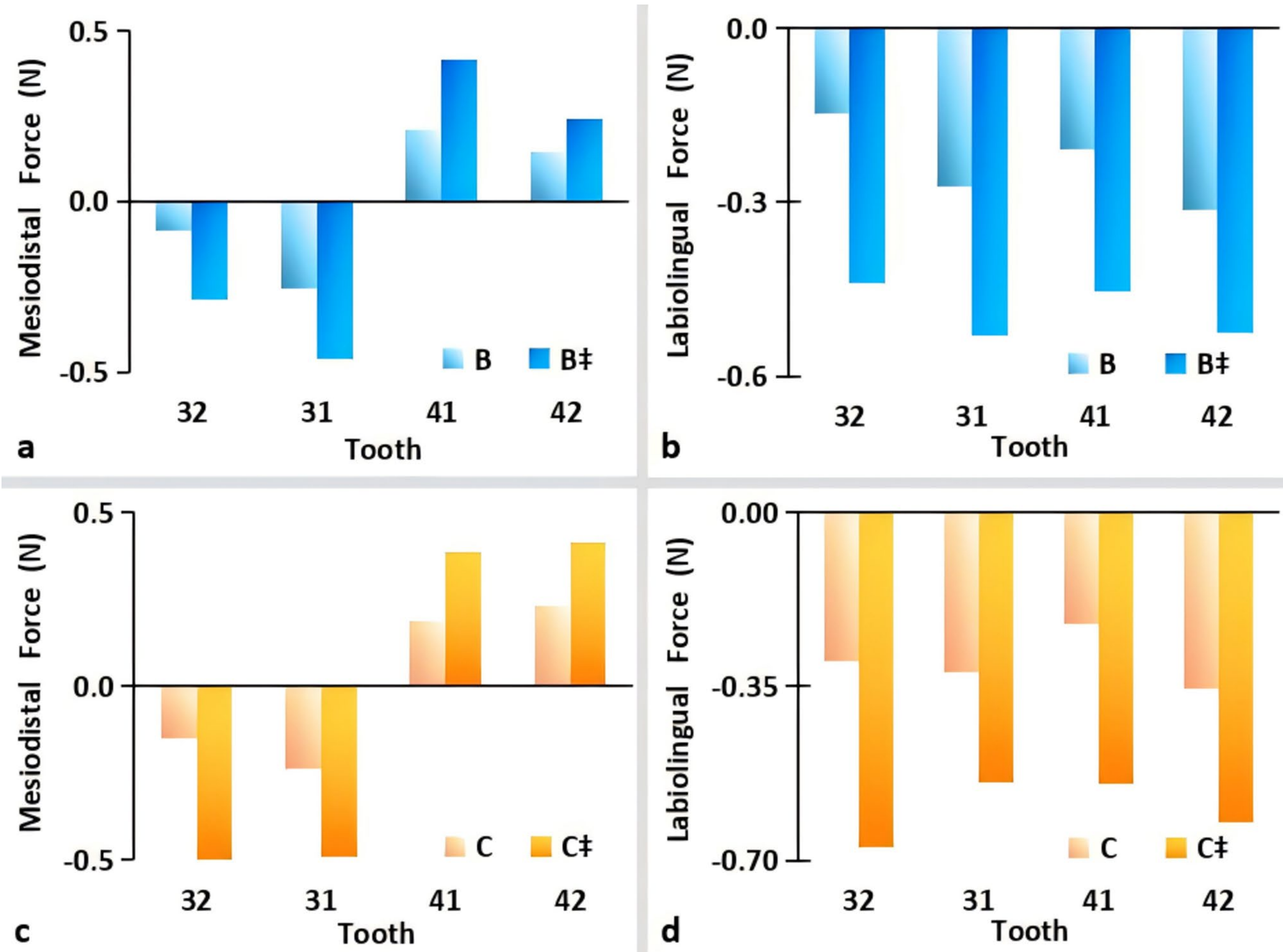

Fig. 3 Mesiodistal and labiolingual forces in Groups B and C before/after thermal reactivation at 24 h. **a** Mesiodistal forces of Group B, **b** Labiolingual forces of Group B, **c** Mesiodistal forces of Group C, **d** Labiolingual forces of Group C (‡ indicates after reactivation)

the left lateral incisor, there were significant differences in lingual forces between the two groups ($P<0.05$) at all time points. Compared to earlier time points, the P-value increased at 60 h, suggesting diminished intergroup differences. Notably, the mesiodistal and vertical forces of group B were not consistently lower than those of group A. Conversely, the mesiodistal forces of the central incisors and the vertical forces of lateral incisors in group B exceeded those in group A with significant intergroup variations at most timepoints.

Since the lingual forces on incisors in group B were significantly lower than those in group A, the step size for Perfitalign 4D aligners was increased to 0.2 mm in group C. Group C exhibited higher lingual forces than group B, although most intergroup differences became non-significant after 4 h. Vertically and mesiodistally, group C did not exhibit greater forces than group B. Conversely, group B produced higher vertical forces on the right lateral incisor and greater mesiodistal forces on the bilateral central incisors. However, the differences between groups B and C were statistically significant only at specific dental positions. Despite the increased step size, group A maintained significantly higher initial lingual forces compared to group C, yet the differences between groups A and C at identical timepoints were smaller than the differences between groups A and B. Similar to group B, group C generally exceeded group A in mesiodistal and vertical forces across most measurements.

Abbreviations and symbols follow Table 3. For Fx (mesiodistal force) and Fy (labiolingual force), values include the PRS for each incisor and the mean PRS across the four incisors. For Fz (vertical force), however, only the individual PRS values are provided for reference, as the mean was excluded due to the substantial measurement uncertainty associated with its low magnitude.

Dynamic force variations and comparison

Based on the PRS in mesiodistal and labiolingual directions (Table 4), we analyzed the dynamic changes in orthodontic forces in each group during mandibular incisor retraction and plotted line charts to visualize the changing trends (Figs. 4 and 5). Group A exhibited

Table 5 Inter-group force comparisons (A vs. B, B vs. C, A vs. C) at selected timepoints

Time		0 h			4 h			12 h			24 h			60 h		
Dir. F	Tooth	AvsB	BvsC	AvsC	AvsB	BvsC	AvsC	AvsB‡	B‡vsC‡	AvsC‡	AvsB‡	B‡vsC‡	AvsC‡	AvsB‡	B‡vsC‡	AvsC‡
Fx	32	0.117	0.047*	0.251	0.009**	0.009**	0.076	0.347	0.117	0.347	0.076	0.047*	0.175	0.251	0.028*	0.016*
	31	0.009**	0.754	0.009**	0.016*	0.754	0.117	0.009**	0.602	0.016*	0.009**	0.347	0.016*	0.009**	0.754	0.009**
	41	0.009**	0.076	0.009**	0.117	0.347	0.175	0.009**	0.465	0.009**	0.016*	0.602	0.016*	0.009**	0.602	0.009**
	42	0.016*	0.009**	0.117	0.009**	0.009**	0.175	0.117	0.175	0.602	0.047*	0.117	0.602	0.009**	0.028*	0.917
Fy	32	0.009**	0.016*	0.016*	0.009**	0.009**	0.016*	0.009**	0.076	0.047*	0.009**	0.028*	0.028*	0.047*	0.047*	0.917
	31	0.009**	0.175	0.009**	0.076	0.347	0.175	0.076	0.754	0.117	0.028*	0.917	0.047*	0.465	0.917	0.602
	41	0.009**	0.009**	0.009**	0.009**	0.251	0.009**	0.009**	0.117	0.009**	0.009**	0.347	0.009**	0.028*	0.175	0.076
	42	0.009**	0.009**	0.009**	0.009**	0.465	0.009**	0.009**	0.465	0.009**	0.009**	0.465	0.009**	0.009**	0.175	0.009**
Fz	32	0.047*	0.175	0.009**	0.175	0.047*	0.009**	0.016*	0.076	0.009**	0.047*	0.117	0.009**	0.465	0.028*	0.009**
	31	0.251	0.117	0.117	0.047*	0.465	0.047*	0.076	0.175	0.754	0.016*	0.016*	0.754	0.009**	0.465	0.047*
	41	0.251	0.465	0.076	0.175	0.465	0.175	0.347	0.602	0.754	0.047*	0.602	0.076	0.602	0.465	0.465
	42	0.016*	0.028*	0.175	0.117	0.047*	0.754	0.028*	0.076	0.602	0.009**	0.047*	0.347	0.009**	0.016*	0.028*

Follow Table 3 for abbreviations and symbols; $^*P < 0.05$, $^{**}P < 0.01$

a pattern of rapid force reduction during the initial 16 h (decay rates influenced by tooth position and force direction), followed by a relative deceleration in the later phase. By 60 h, mesiodistal forces decreased to an average of 48.84% (35.27 ~ 67.66%) of the baseline value, and labiolingual forces decreased to an average of 54.25% (46.64 ~ 63.76%). In groups B and C, thermal reactivation demarcated cyclic “recovery—decay—recovery” patterns with no significant intergroup differences. Both groups revealed faster initial decay rates (0 ~ 4 h) than group A. Except for a few cycles, the majority of force attenuation occurred within the first 4 h of each reactivation cycle.

Comparison of movement trends in mandibular incisors

During retraction, the incisors as target teeth were primarily subjected to lingual forces. Based on force-moment coupling analysis, labiolingual forces (Fy) induced rotational moments around the x-axis (Mx). The incisor movement tendency was evaluated based on the Mx/Fy ratio (Table 6). Given substantial force decay over time (Table 4), diminished force magnitudes after 0 h could compromise the reliability of this ratio. Thus, only initial (0 h) values were analyzed. The results revealed lower Mx/Fy ratios in groups B and C compared to group A. In addition, group B exhibited smaller ratios compared to group C.

Discussion

Clear aligners are fabricated from thermoplastic polymers. The viscoelastic nature of the material results in high initial stress and rapid stress relaxation under mechanical load. In vitro experiments showed that the initial stress applied to the maxillary second premolar during bodily movement in the buccolingual direction reached 1.8 ~ 2.0 N, 3.0 N for extrusion and 2.4 N for intrusion. These values were significantly greater than the recommended threshold (0.1 ~ 1.2 N) [6]. Li et al. [32] indicated that the orthodontic force generated by clear aligners exhibits substantial variation in the initial stage, requiring a transition period of 3 ~ 5 days to stabilize. This high initial stress impact may potentially undermine periodontal health.

Periodontitis is the sixth most prevalent chronic disease globally, affecting approximately 60% of adults globally [33]. Due to the loss of periodontal supporting tissues, teeth struggle to withstand normal masticatory forces and forces from the labial/lingual musculature. Pathological migration of anterior teeth occurs in up to 30~56% of patients with periodontitis [34]. Malpositioned teeth are more susceptible to plaque formation and occlusal trauma, which can accelerate periodontal tissue destruction. After controlling periodontal inflammation, orthodontic treatment can improve dental function and aesthetic features, achieving more

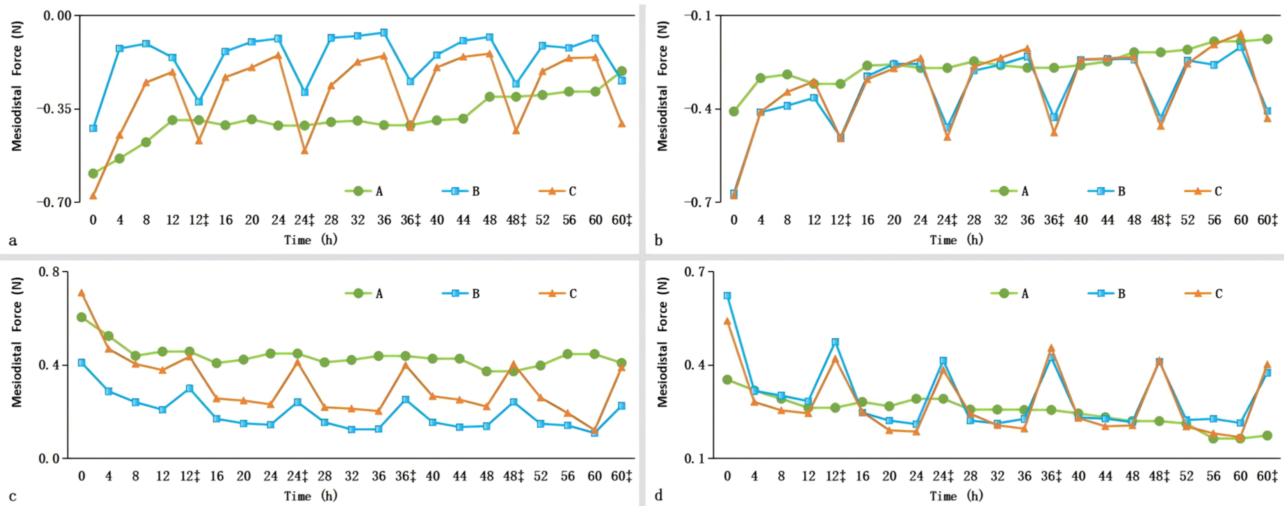

Fig. 4 Longitudinal variations in mesiodistal forces during incisor retraction. **a** Mandibular left lateral incisor, **b** Mandibular left central incisor, **c** Mandibular right lateral incisor, **d** Mandibular right central incisor (Symbols follow Fig. 3. Group A exhibited identical force values at ‡-labeled and corresponding non-‡ timepoints)

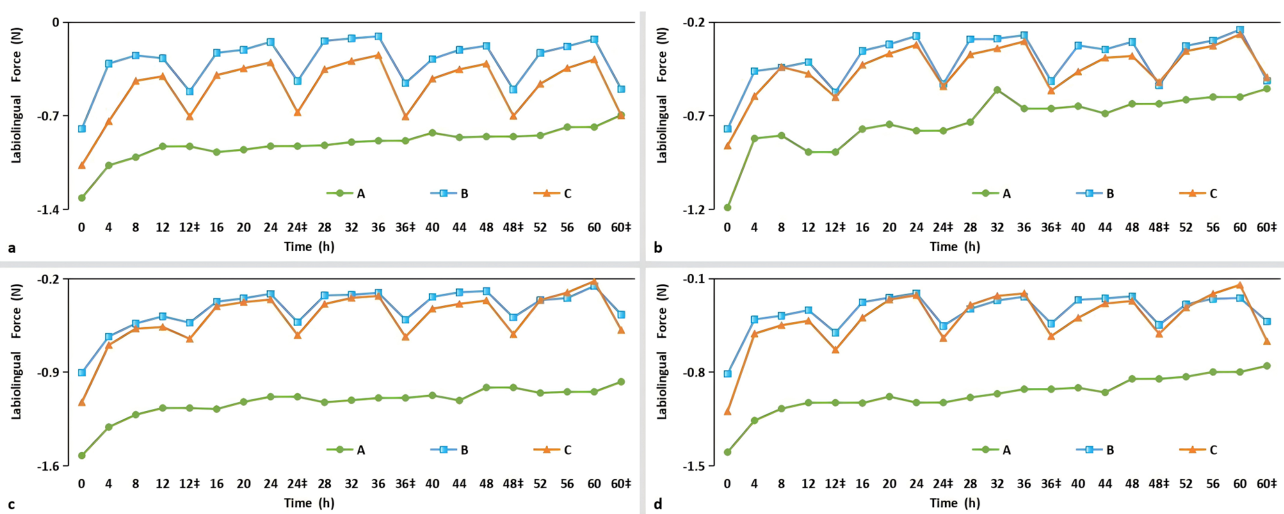

Fig. 5 Longitudinal variations in labiolingual forces during incisor retraction. **a** Mandibular left lateral incisor, **b** Mandibular left central incisor, **c** Mandibular right lateral incisor, **d** Mandibular right central incisor (Symbol definitions and group A data processing are identical to Fig. 4)

Table 6 Mx/Fy ratios at 0-hour

Tooth	31			41		
Group	Fy(N)	Mx(N.mm)	Mx/Fy(mm)	Fy(N)	Mx(N.mm)	Mx/Fy(mm)
A	− 1.190 ± 0.071	12.599 ± 2.032	− 10.669 ± 2.095	− 1.397 ± 0.069	13.934 ± 2.056	−10.011 ± 1.616
B	− 0.770 ± 0.070	2.545 ± 0.654	− 3.296 ± 0.775	− 0.811 ± 0.092	5.546 ± 2.021	− 6.807 ± 2.301
C	− 0.859 ± 0.086	7.539 ± 2.651	− 8.740 ± 2.588	− 1.093 ± 0.091	8.309 ± 1.532	− 7.629 ± 1.420
Tooth	32			42		
Group	Fy(N)	Mx(N.mm)	Mx/Fy(mm)	Fy(N)	Mx(N.mm)	Mx/Fy(mm)
A	− 1.314 ± 0.067	10.831 ± 7.888	− 8.384 ± 6.499	− 1.523 ± 0.085	12.281 ± 1.279	− 8.043 ± 0.432
B	− 0.796 ± 0.093	2.737 ± 0.478	− 3.505 ± 0.822	− 0.903 ± 0.062	5.464 ± 0.116	− 6.075 ± 0.422
C	− 1.069 ± 0.090	5.717 ± 1.438	− 5.392 ± 1.518	− 1.124 ± 0.087	7.551 ± 0.569	− 6.724 ± 0.270

stable outcomes. However, due to reduced vertical alveolar bone height, the CR of affected teeth shifts apically, which leads to an increased moment under the same orthodontic force and increases the risks of uncontrolled tipping movement and root resorption [35, 36]. Finite element studies confirmed that under identical force application methods, teeth with reduced periodontal support exhibit greater movement magnitude and higher periodontal ligament stress compared to teeth with normal periodontal support [37, 38]. Therefore, clear aligner treatment plans need to reduce the step size to lower the orthodontic force. This compensates for the elevated periodontal stress caused by reduced periodontal tissue and helps maintain the periodontal health of patients. Our previous studies have shown that for patients with alveolar bone height reduction ≥ 1/3, the step size for intrusion of mandibular incisors should not exceed 0.15 mm [39]. Given the diminished tolerance to orthodontic forces in patients with reduced periodontal support, the initial high stress of clear aligners is more likely to introduce damage. Therefore, this study focused on this population. The step size for thermoformed aligners was 0.15 mm, below the conventional range of 0.2 ~ 0.30 mm. Retrospective studies have reported that mandibular incisors, as the teeth with the smallest root surface area in the dentition, exhibit the highest root resorption rate during combined periodontal-orthodontic treatment [35]. Precise control of orthodontic forces in this region is critical to avoiding adverse effects. Therefore, mandibular incisors were regarded as both the target teeth for movement and the research subject in this study.

The fabrication of thermoformed aligners relies on physical models. After thermoforming, undercuts on the model often cause demolding difficulties and forcible removal may damage the aligner. Therefore, blockout materials must be applied to fill model undercuts in advance, forming a smooth transitional surface. However, this strategy compromises the aligner retention force. During anterior retraction, posterior attachments are typically added to maintain intimate contact between the aligner and tooth surfaces while preventing mesial tipping of posterior teeth [40, 41]. The fabrication of 4D aligners resolves the need for the molding and demolding processes essential to conventional thermoforming. Within the digital workflow, only undercuts interfering with insertion/removal are adjusted, significantly enhancing the retention force compared to thermoformed aligners. This strategy reduces or even resolves the need for attachments [42, 43]. Given that teeth with reduced periodontal support inherently lack sufficient retention, attachments can increase instantaneous stress during insertion/removal, potentially exacerbating tooth mobility. Therefore, in this study, no attachments were designed in the Perfitalign 4D aligners. To control variables, identical designs were applied to thermoformed aligners.

The results of repeated insertion/removal test (Table 1) indicated high test-retest reliability. Although deformation of the aligner and subtle variations in operator handling during 15 repeated insertion/removal cycles led to fluctuations in measurement results, changes in force values remained within clinically acceptable limits (ICC > 0.9), suggesting that this frequency of insertion/removal did not significantly affect force measurement outcomes. For all experimental groups, intra-group force measurement errors encompassed both measurement errors and aligner fabrication errors. Therefore, ICC values were comparatively lower than those obtained from repeated tests (Table 2) but still higher than 0.9. This finding confirms that fabrication errors were effectively controlled at a low level. More importantly, no difference was observed between thermoformed aligners and Perfitalign 4D aligners in terms of this metric, suggesting comparable stability between the two manufacturing processes. These findings indicate that the 3D printing technique introduced no additional process-induced variations that could significantly compromise intra-group measurement consistency.

Excessive orthodontic forces may induce capillary collapse or complete occlusion in the periodontal ligament, impairing local microcirculation and leading to ischemia. This increases the risk of root resorption and reduces tooth movement velocity [44–46]. However, safe force thresholds with reduced periodontal support remain undefined, with limited studies available. Some scholars proposed using the maximum von Mises stress in periodontal tissues as a benchmark, suggesting that for mandibular second premolars with periodontal tissue defects (loss ≤ 8 mm), orthodontic forces should not exceed 0.6 N during bodily movement, tipping, or rotation [47]. Another study recommended that compared to normal teeth, for maxillary incisors with reduced alveolar bone height, retraction and intrusion forces should be reduced by 20% (to 160 g total for four incisors) and 25% (to 60 g total for four incisors), respectively, to limit periodontal ligament strain to less than the critical threshold of 20% [48]. Given that the teeth investigated in previous studies differ from those investigated in our study, it is challenging to assess whether the orthodontic forces applied in each group were appropriate for patients with reduced periodontal support. However, throughout the experimental period, group B was subjected to significantly lower lingual forces on mandibular incisors compared to group A, with the initial lingual forces ranged from 0.770 to 0.903 N (Tables 3 and 5), which falls closer to the safety ranges proposed in previous studies. Moreover, group B exhibited more rapid force decay (Table 4), suggesting that for equivalent step size, Perfitalign 4D aligners achieve tooth movement with lower initial stress than conventional aligners, thereby mitigating the impact of high stress on periodontal tissues.

For patients with reduced periodontal support, clear aligner treatment protocols can address their low-force requirements by reducing step sizes, thereby prolonging treatment duration. Prolonged treatment and aligner-induced challenges in oral hygiene maintenance increase the risk of inflammation [49]. Furthermore, thermoformed aligner materials deliver optimal stress when undergoing deformation of 0.2 ~ 0.5 mm. Reducing tooth movement increments may compromise their mechanical efficacy [50]. Experimental data indicated that even when the step size was increased to 0.20 mm, the lingual forces of Perfitalign 4D aligners on incisors remained lower than those of conventional aligners with a 0.15 mm step size during the initial 60 h (Table 3). Therefore, when using thermoformed aligner forces as the design reference, the step size of Perfitalign 4D aligners can appropriately increase. This approach may enhance tooth movement efficiency, thereby reducing the number of aligners required and lowering treatment costs.

Mesiodistal forces in Perfitalign 4D aligners showed no significant reduction (Table 3) and even significantly exceeded those of thermoformed aligners at a specific tooth (Table 5). This may be attributed to their superior retention force. Since no tooth movement was designed in this direction, increasing the step size did not affect orthodontic forces, resulting in similar force values in groups B and C. Inadequate retention in thermoformed aligners reduces friction between the aligner and tooth surfaces, limiting mesiodistal forces on incisors. Therefore, group A exhibited lower mesiodistal forces. This observation is consistent with the Mx/Fy ratios at 0 h. Measurements revealed that the CR of mandibular incisors in this model was located 7.1 ~ 7.5 mm apical to the crown center. Since forces and moments were transferred to the CR, an Mx/Fy ratio closer to zero suggests that the tooth movement is closer to bodily movement, whereas ratios exceeding 7.1 ~ 7.5 mm indicate uncontrolled tipping. In contrast, Perfitalign 4D aligners exhibited tooth movement that more closely conformed to the design, which may be attributed to the purported superior retention[36,37]. All Mx/Fy ratios in group B were less than the threshold (7.1 ~ 7.5 mm), suggesting that the tooth movement in this group was closer to bodily movement than that in group A. Although group C showed a greater tipping tendency than group B due to increased step size, it still outperformed group A. However, further studies are still needed to investigate whether the elevated mesiodistal forces in Perfitalign 4D aligners can induce clinically undesired tooth movement. Additionally, although Perfitalign 4D aligners exerted more favorable forces at the initial time point (0 h) than thermoformed aligners, their superiority in controlling incisor labiolingual inclination needs further clinical studies due to significant time-dependent changes in the force-related behavior of both types of aligner.

The fundamental differences between 4D aligners and thermoformed aligners lie in their unique biomechanical features driven by shape-memory properties. Orthodontic forces from Perfitalign 4D aligners decrease rapidly but can largely recover through thermal reactivation. During the 60-hour observation period, Perfitalign 4D aligners with different step sizes exhibited similar force delivery patterns (Figs. 4 and 5). This force application mode differed significantly from thermoformed aligners or Tera Harz TC-85 aligners. Thermoformed aligners demonstrated a rapid initial decay in orthodontic force, which subsequently decelerated in the later phase. Studies have shown that under 37 °C/100% humidity, aligner foils exhibit stress relaxation rates of 17.9–62% after 24 h and 63.1–96.1% after 14 days [2, 51]. These values vary with material composition and laminate layers, often resulting in excessive initial forces, followed by insufficient late-stage forces. Tera Harz TC-85 aligners generate high initial stress but suffer from rapid force decay. Since they can recover the original shape at 37 °C, they show biomechanical behavior similar to that of thermally activated nickel-titanium archwires, maintaining relatively consistent orthodontic forces in the oral cavity [1]. Although force magnitudes fluctuate throughout the treatment cycle, forces exerted by both aligners can be classified as continuous forces, whereas Perfitalign 4D aligners exhibit force application patterns closer to intermittent forces.

Clinical studies confirmed that at equivalent magnitudes, intermittent forces more effectively stimulate bone remodeling and reduce root resorption and undesired tooth movement compared to continuous forces [52–55]. Navarrete et al. [56] reported that anterior teeth with reduced periodontal support tolerate intermittent light forces well, with no significant changes in the levels of inflammatory biomarkers, including IL-6, IL-17 A, and MMP-8, in gingival crevicular fluid throughout the treatment period. Some scholars propose that intermittent forces provide reparative intervals for periodontal tissues during force-off periods, supporting physiological tooth movement [57]. Although thermoformed aligners exhibit force intermittency when removed during meals, the daily wear for more than 22 h results in insufficient unloading periods (< 2 h/day). Such brief stress-free intervals may not be conducive to adequate periodontal tissue repair [58]. Previous intermittent force protocols required fixed appliances, necessitating frequent reactivation appointments. During unloading phases, passive archwires had to be bent and installed to prevent relapse, which is a technique-sensitive and time-consuming

Table 7 Vertical forces on canines and premolars at 0 and 4 h

Tooth	Values (mean ± SD unit: *N*) at 0 h			Values (mean ± SD unit: *N*) at 4 h		
	A	B	C	A	B	C
35	− 0.058 ± 0.158	− 0.239 ± 0.146	− 0.184 ± 0.070	0.070 ± 0.093	− 0.210 ± 0.084	−0.149 ± 0.087
34	− 0.277 ± 0.094	− 0.753 ± 0.182	− 0.745 ± 0.212	− 0.217 ± 0.112	− 0.361 ± 0.063	−0.298 ± 0.085
33	0.150 ± 0.127	0.467 ± 0.040	0.450 ± 0.076	0.118 ± 0.026	0.273 ± 0.055	0.228 ± 0.087
43	− 0.032±− 0.033	− 0.574 ± 0.049	− 0.424 ± 0.088	− 0.051 ± 0.074	− 0.282 ± 0.050	−0.204 ± 0.030
44	− 0.005 ± 0.094	0.218 ± 0.041	0.261 ± 0.096	0.045 ± 0.066	0.131 ± 0.054	0.098 ± 0.023
45	− 0.386 ± 0.112	− 0.263 ± 0.068	− 0.322 ± 0.058	− 0.202 ± 0.027	− 0.187 ± 0.051	−0.094 ± 0.051

process [53, 55, 59]. In contrast, patients can independently reactivate Perfitalign 4D aligners through thermal stimulation without professional intervention. Moreover, with Perfitalign 4D aligners, unintended tooth displacement during force-off periods can be effectively prevented.

It should be noted that several studies have reported reduced tooth movement efficiency with intermittent forces compared to continuous forces under equivalent treatment durations [53, 59, 60]. However, the efficiency of intermittent force systems was found to be regimen-dependent. Yildiz et al. [57] applied intermittent forces to canines via a Hycon device, revealing differential distalization distances across force application regimens despite identical cumulative activation. Meanwhile, animal experiments have shown that compared to continuous forces, daily force application for 8 h recruits osteoclasts more effectively on the pressure side [52]. Given that the force application regimen of Perfitalign 4D aligners differs from those reported in previous studies and considering the inherent force decay in thermoformed aligners, subsequent clinical trials should compare their tooth movement efficiency.

Despite the significant advantages of Perfitalign 4D aligners in reducing stress in periodontal tissues during the initial hours of wear, vertically directed intrusive forces may be higher than desired (Table 3). This may originate from inherent limitations in the 3D printing process. Perfitalign 4D aligners are produced by layerwise photopolymerization of liquid resin under projected light. Despite mechanical resin removal after printing, complex anatomical regions, such as cusps of canines and premolars, often remain uncured resin. This resin undergoes continued polymerization after curing, leading to localized thickening of the aligner [1, 14]. Therefore, the crown height of the aligner will be shorter than the crown height of the actual tooth, generating intrusive forces. Perfitalign 4D aligners exerted substantial intrusive forces on the left first premolar and right canine at 0 h, inducing reactive forces on adjacent teeth (Table 7). However, their rapid force attenuation characteristics mitigated the effect of this aberrant biomechanical pattern, evidenced by significantly reduced intrusive forces at 4 h. While acute tissue damage is unlikely, long-term effects necessitate validation through in vivo studies.

This study faced several limitations. First, all tests were conducted at room temperature without simulating intraoral conditions, periodontal tissues, or dynamic tooth movement. Since the mechanical properties of clear aligners are temperature-, humidity-, and strain-dependent (the latter correlates with tooth movement), in vitro force measurements do not fully represent orthodontic forces in the oral cavity. Second, the effect of occlusal forces on the mechanical behavior of aligners was not considered in this study. Third, the observation period in this study was limited to 60 h, far shorter than the actual clinical wearing duration per aligner. Thus, the findings mainly characterize the force-related behavior in the initial phase of wear. Future studies should extend the length of observation, especially for measuring the effect of multiple thermal activation cycles on the force recovery of the Perfitalign 4D aligner. Finally, due to differing attachment requirements between thermoformed and Perfitalign 4D aligners, we designed no attachments to maintain controlled variable conditions. However, in clinical practice, thermoformed aligners typically require posterior attachments during anterior retraction. Their deliberate omission in this study may have compromised the force-related behavior of thermoformed aligners. For instance, Fan et al. [61] reported lower forces on incisors in the absence of attachments during retraction. Future studies should establish models incorporating attachments for further validation.

Conclusions

1. Perfitalign 4D aligners exhibited significant orthodontic force recovery after thermal reactivation, though a slight downward trend was observed over five reactivation cycles within 60 h. Residual stress percentages after reactivation were similar across different step sizes, suggesting that the designed step size variations did not affect shape-memory-driven mechanical behavior.
2. Throughout the experimental period, Perfitalign 4D aligners exerted significantly lower lingual forces on incisors than thermoformed aligners—a difference

observed even with increased step sizes. This finding suggests that Perfitalign 4D aligners can reduce lingual loading while permitting larger movement increments, though their elevated mesiodistal and vertical forces warrant attention.

3. Perfitalign 4D aligners establish a unique intermittent force application pattern through rapid stress attenuation and thermal reactivation recovery.
4. Perfitalign 4D aligners more comprehensively achieved the designed tooth movement. Compared to thermoformed aligners, Perfitalign 4D aligners showed significantly lower incisor Mx/Fy ratios, closer to bodily movement during anterior retraction, while smaller step sizes may further optimize the biomechanical control.

Supplementary Information

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Supplementary Material 1. Table S1 Force measurement results after 15 insertion/removal cycles of differently designed aligners. Table S2 Verification of intra-specimen consistency of identically designed aligners.

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Author contributions
J.X. conducted all experiments, performed data curation and statistical analysis, and drafted the initial manuscript. Y.M. conceived and designed the study, and provided guidance on the interpretation of the results. R.Q. assisted with data curation and statistical analysis. X.F. and M.Z. participated in the preparation of figures and tables. Z.J. conceived and designed the study, reviewed and approved the final version of the manuscript, and acquired the funding for the research. All authors reviewed the manuscript.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
The experimental protocol was approved by the Ethics Committee of the Third Hospital Affiliated of Air Force Military Medical University (Approval No. KQ-YJ-2025-197) and strictly adhered to the principles of the Declaration of Helsinki for human subject research.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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