Influence of thermoplastic appliance thickness on the magnitude of force delivered to a maxillary central incisor during tipping

Wolfram Hahn,[a] Henning Dathe,[b] Julia Fialka-Fricke,[b] Susanne Fricke-Zech,[b] Antonia Zapf,[c] Dietmar Kubein-Meesenburg,[d] and Reza Sadat-Khonsari[a]
Göttingen, Germany

Introduction: The aim of the study was to quantify the forces delivered by thermoplastic appliances made of 2 materials with 2 thicknesses to a maxillary central incisor during tipping. **Methods:** Two materials were tested, each in 2 thicknesses: Erkodur (Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany) 1.0 and 0.8 mm, and Biolon (Dreve Dentamid GmbH, Unna, Germany), 1.0 and 0.75 mm. For each material, 5 appliances were produced. To measure the forces applied, an isolated measuring tooth, part of a standardized resin model, was deflected in 0.05° steps from 0° to 0.42° in the vestibular and palatine directions, after placing the respective appliance on the model. For statistical analysis, the force components Fx/tipping and Fz/intrusion at a displacement of ± 0.151 mm from the incisor edge were selected. Means and standard deviations were calculated. The Wilcoxon 2-sample test for group pairings was used. **Results:** The norms for the mean Fx forces ranged from 1.62 (SD, 0.41) to 5.35 N (SD, 0.63). The mean Fz forces were between 0.07 (SD, 0.13) and −2.47 N (SD, 0.34). The highest intrusive forces were measured during vestibular displacement of the measuring tooth. The forces delivered by the thick appliances were overall significantly higher (P <0.0001) than those of the thin materials. The forces delivered by the Biolon appliances were generally significantly higher (P <0.0001) than those for the Erkodur materials. **Conclusions:** The forces applied were mostly too high when compared with those stated in the literature as ideal. In addition to thickness, the thermoforming process influences the magnitude of the force delivered by a thermoformed appliance. (Am J Orthod Dentofacial Orthop 2009;136:12.e1-12.e7)

As a result of increased interest in adult orthodontic treatment, esthetic alternatives to conventional fixed appliances are often requested. Therefore, various types of thermoplastic appliances have been introduced in orthodontics.

The technique was originally introduced by Kesling[1] and subsequently improved as an alternative or a supplement to fixed appliances.[2,3]

For the commercial ClearSmile system (ClearSmile Pty Ltd, Keiraville, Australia), a dental technician resets the teeth on a plaster model by hand and forms an overlay appliance for every desired step of tooth movement.[4]

From the Georg-August-University of Göttingen, Göttingen, Germany.
[a] Assistant professor, Department of Orthodontics.
[b] Staff member, Department of Orthodontics.
[c] Staff member, Department of Medical Statistics.
[d] Head, Department of Orthodontics.
The authors report no commercial, proprietary, or financial interest in the products or companies described in this article.
Reprint requests to: Wolfram Hahn, Department of Orthodontics, Georg-August-University Göttingen, Robert-Koch-Strasse 40, D-37099 Göttingen, Germany; e-mail, weahahn@aol.com.
Submitted, October 2008; revised and accepted, December 2008.
0889-5406/$36.00

doi:10.1016/j.ajodo.2008.12.015

Align Technology (Santa Clara, Calif) uses a series of computer-generated thermoplastic appliances constructed on stereolithographic models.[5,6] Despite documentation of successful treatments, the force delivery properties of various appliances have still not been systematically investigated, and only a few studies have been published on this topic.[7-9]

The forces imparted by a thermoplastic appliance to a maxillary first premolar in vivo were measured by Barbagallo et al[4] using a pressure-film approach.

One study was published recently concerning the influence of thickness of the appliances on force delivery.[10] In this study, 3-point bending and recovery tests were performed on standardized, flat specimens.

The aim of our study was to quantify the force components with focus on the tipping and intrusive forces generated by removable thermoplastic appliances made of 2 hard thermoplastic materials with 2 thicknesses on a maxillary central incisor during tipping.

MATERIAL AND METHODS

We recently developed a modular force-torque device for measuring forces in orthodontic research. It

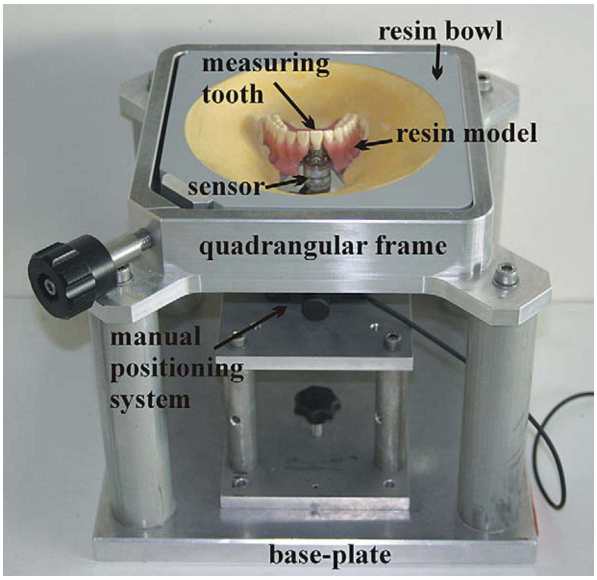

Fig 1. Basic components of the measuring device.

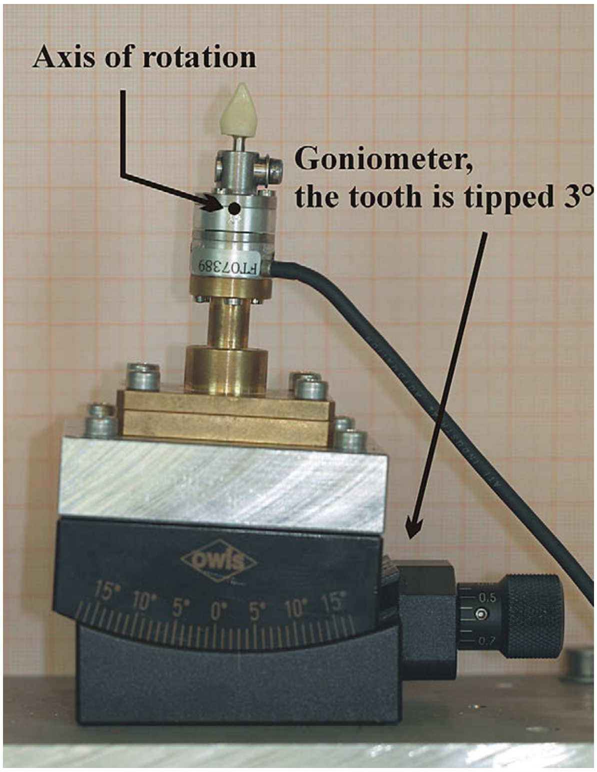

Fig 2. The measuring tooth is tipped 3° vestibularly by the goniometer. The axis of rotation is located at the virtual apex.

consists of a quadrangular frame fixed on a baseplate by 4 columns. These units are all made of hard aluminum. A resin bowl can be fixed in the frame and reversed in the same position and fixed with a locking screw.

In the resin bowl, a standardized resin model (Frasaco GmbH, Tettnang, Germany) with the separated measuring tooth was fixed with plaster. The measuring tooth was fixed reversibly on the sensor. For reproducible positioning of the tooth, a plaster key was used (Fig 1).

The sensor was fixed on a manual positioning system. To simulate tipping motion sequences, a goniometer (GO 90-W30, OWIS GmbH, Staufen, Germany) was used. To simulate pure tipping displacement, the measuring tooth of the resin model was orientated perpendicular with its incisor edge to the direction of motion. The rotational axis of the measuring tooth was adjusted at the calculated apex. The manual positioning system was once more fixed by an aluminum frame on the baseplate (Figs 1 and 2).

The entire measuring device could be placed under a drying chamber, which had a hole in its bottom, to simulate 37°C temperature (Fig 3).

The sensor was a Nano 17 (ATI Industrial Automation, Apex, NC) that measured all 6 components of force and torque (Fx, Fy, Fz, Tx, Ty, and Tz) (Fig 4).

We used the calibration provided by the manufacturer with 1% full-scale accuracy. This calibration offers sensing ranges in the optimal measuring ranges of ±12 N for Fx and Fy, ±17 N for Fz, and ±120 Nmm for Tx, Ty, and Tz, respectively. The Nano 17 transducer has hardware temperature compensation to stabilize its sensitivity to approximately ±25°C in relation to room temperature.

After installation of the measuring device, an impression (Tetrachrom, Kanidenta, Herford, Germany) of the model with the measuring tooth in the neutral position was taken, and then a plaster model was made by using GC Fujirock EP (GC Germany GmbH, Munich, Germany). The plaster model was trimmed to a height of 20 mm parallel to the occlusal plane, and 20 identical plaster copies (with GC Fujirock EP) were made by using Adisil blue 9:1 (Siladent, Dr Böhme & Schöps GmbH, Goslar, Germany). From each material to be evaluated, 5 appliances extending to the gingival margin were made from these models. The materials were Erkodur 1.0 and 0.8 mm (Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany) and Biolon 1.0 and 0.75 mm (Dreve Dentamid GmbH, Unna, Germany). The Erkodur blanks were formed with Erkoform RVE (Erkodent Erich Kopp GmbH), and Drufomat-TE (Dreve Dentamid GmbH) was used for the Biolon blanks. Measurements were made at 37°C in the drying chamber. The inner surface of the appliance was moistened with artificial saliva (University-Pharmacy, Göttingen, Germany). Before starting the actual measuring cycle, the forces and moments were set to zero.

Fig 3. The entire measuring device is placed under a drying chamber, which has a hole in its bottom.

For the measurements, the tooth was tipped in the vestibular and palatine directions from 0° to 0.42° (24.9 arcmin) and back to 0° in 0.05° (2.7 arcminutes) steps. The measurements were recorded 5 times after each step movement. Angular degrees were converted into movement range in millimeters from the inicisor edge.

Because of overload protection of the sensor, the incisor edge could be maximally deflected up to 0.151 and –0.151 mm in all cases. This activation range is equivalent to the lowest value of the activation range documented in the literature for a thermoplastic appliance system (Invisalign, Align Technology).[11] Statistical analysis was done with SAS software (SAS Institute, Cary, NC). The force components Fx (horizontal force component/tipping) and Fz (vertical force component/intrusion) for an activation range of ±0.151 mm were used for further analysis. Means and standard deviations were calculated.

The corresponding samples were compared by using the Wilcoxon 2-sample test. When a test against zero was applied, we used the signed-rank test.

RESULTS

Typical measured forces for Fx and Fz are shown in Figure 5 for 1 material (Biolon, 1.0 mm). Hysteresis

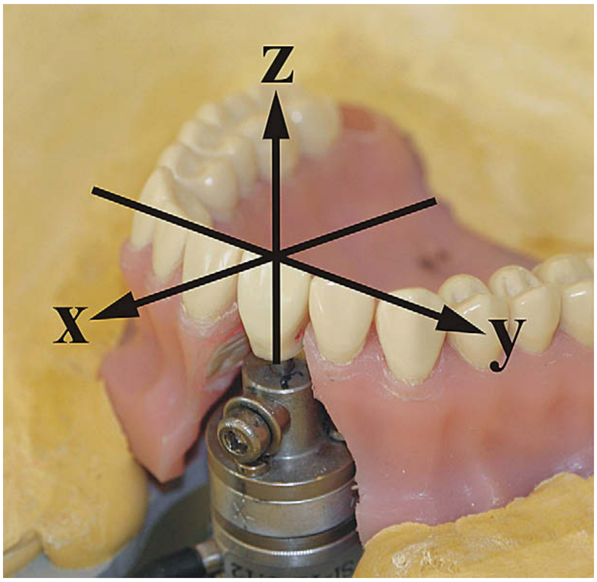

Fig 4. The z-axis runs through the center of the incisor edge and the apex. The x-axis is orientated perpendicularly to the incisor edge and parallel to the direction of motion of the goniometer.

effects were observed, but these were excluded from this discussion, because the maximum deflection of ±0.151 mm, in which hysteresis effects are negligible, was used for further analysis.

The means and standard deviations for Fx and Fz forces at deflections of ±0.151 mm are given in Table I for each material. The comparisons of the corresponding samples with the Wilcoxon 2-sample test are shown in Table II. The corresponding box plots are shown in Figure 6.

Because of the overload protection of the sensor, some values for the Biolon appliances are missing. Thus, it can be assumed that the mean force values in these groups would tend to be even higher than those shown in Table I. More often than not, the thickness of the material had a highly significant influence on the forces delivered by a particular appliance. Only for Fx and Fz palatine, when Biolon 1.0 and 0.8 mm were compared, was this influence not observed.

In all cases (except for Fz palatinal, Biolon 1.0 mm vs Erkodur 1.0 mm; $P = 0.3961$), the Biolon appliances produced stronger forces that were highly significant compared with the Erkodur appliances, irrespective of the thickness of the material. Moreover, even the thin Biolon appliance produced mean higher Fx and Fz forces, except for Fz palatine, than the thick Erkodur appliances, irrespective of the direction of the displacement (Tables I and II). The values for Fz were highly

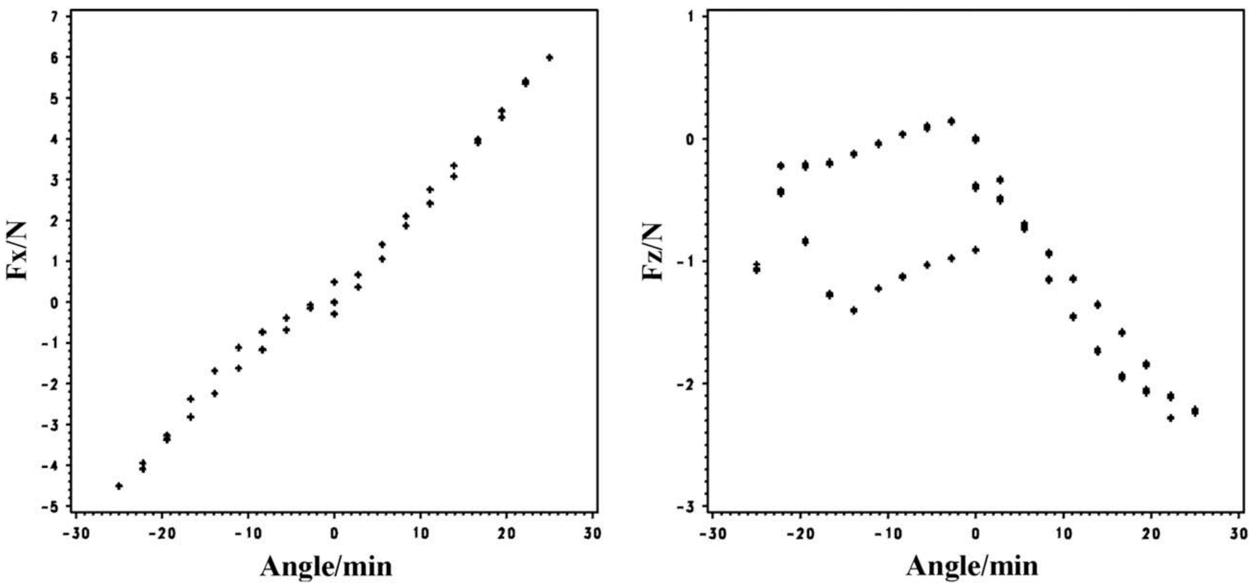

Fig 5. Typical forces measured for Fx and Fz as a function of the displacement of the measuring tooth recorded for 1 material (Biolon, 1.0 mm). For Fx, a small hysteresis phenomenon (reduction in the force delivered during removal of a load compared with the loading phase with the same tooth displacement) was observed. This effect was more pronounced for Fz.

significantly different from zero for the Biolon 1.0 and 0.8 mm and the Erkodur 1.0 mm appliances, but not for the Erkodur 0.75 mm appliance, during palatal displacement. This shows an intrusive force that is stronger in the vestibular displacement direction of the tooth than in the palatine direction (Fig 6).

DISCUSSION

Our measuring device is comparable to many others used in orthodontic research. The shortcoming of this kind of force measurement is the lack of simulation of the periodontal ligament (PDL). These circumstances do not totally allow, for example, the investigator to deduce the force decay from the measured values as would happen under in-vivo conditions after loading as a consequence of tooth movement. Hence, this restricts the value of the results as relevant for forces, since they appear immediately after loading when, because of the viscoelastic property of the PDL, no pronounced rapid tooth movement can be expected.[12,13]

Unfortunately, because of the complex multi-phasic properties of a PDL after loading, a coherent concept for relating the force system to tooth movement and the reaction of the different parts of the PDL have not yet been presented.[14,15]

Nevertheless, the load-deflection characteristics with the observed hysteresis, shown in Figure 5, especially for Fz, might provide an approximation for possible force decay in relation to the distance moved by the tooth after application of a load. But, because the amount of tooth displacement is often higher in a clinical situation, it is difficult to assess whether hysteresis will be comparable with the clinical situation.

The blanks for thermoplastic appliances described in the literature are mainly polyethylene or polypropylene

Table I. Means and standard deviations for Fx and Fz at deflection ranges of ±0.151 mm for the measured materials

Movement range	*Material thickness (mm)*	*Material*	*N*	*Variable*	*Mean*	*SD*
−0.151 mm palatinal tipping of the measuring tooth	0.75	Biolon	10	Fx	−3.96	0.11
	0.75	Biolon	10	Fz	−0.45	0.11
	0.8	Erkodur	50	Fx	−1.62	0.42
	0.8	Erkodur	50	Fz	0.07	0.12
	1	Biolon	25	Fx	−3.88	0.41
	1	Biolon	25	Fz	−0.40	0.38
	1	Erkodur	50	Fx	−2.38	0.53
	1	Erkodur	50	Fz	−0.33	0.41
+0.151 mm vestibular tipping of the measuring tooth	0.75	Biolon	50	Fx	4.10	0.62
	0.75	Biolon	50	Fz	−1.69	0.87
	0.8	Erkodur	50	Fx	2.48	0.48
	0.8	Erkodur	50	Fz	−0.81	0.21
	1	Biolon	45	Fx	5.35	0.63
	1	Biolon	45	Fz	−2.47	0.34
	1	Erkodur	50	Fx	3.14	0.22
	1	Erkodur	50	Fz	−1.16	0.22

Table II. Significance values calculated for comparison of the forces delivered by the appliances in both directions of displacement

		Palatine		Vestibular	
Materials	*Test used*	*Fx (*P *value)*	*Fz (*P *value)*	*Fx (*P *value)*	*Fz (*P *value)*
Biolon 1.0 vs Biolon 0.75	Wilcoxon 2-sample	1.0	0.0706	<0.0001	<0.0001
Erkodur 1.0 vs Erkodur 0.8	Wilcoxon 2-sample	<0.0001	<0.0001	<0.0001	<0.0001
Biolon 1.0 vs Erkodur 1.0	Wilcoxon 2-sample	<0.0001	0.3961	<0.0001	<0.0001
Biolon 0.75 vs Erkodur 0.8	Wilcoxon 2-sample	<0.0001	<0.0001	<0.0001	<0.0001
Biolon 0.75 vs Erkodur 1.0	Wilcoxon 2-sample	<0.0001	<0.3262	<0.0001	<0.0160

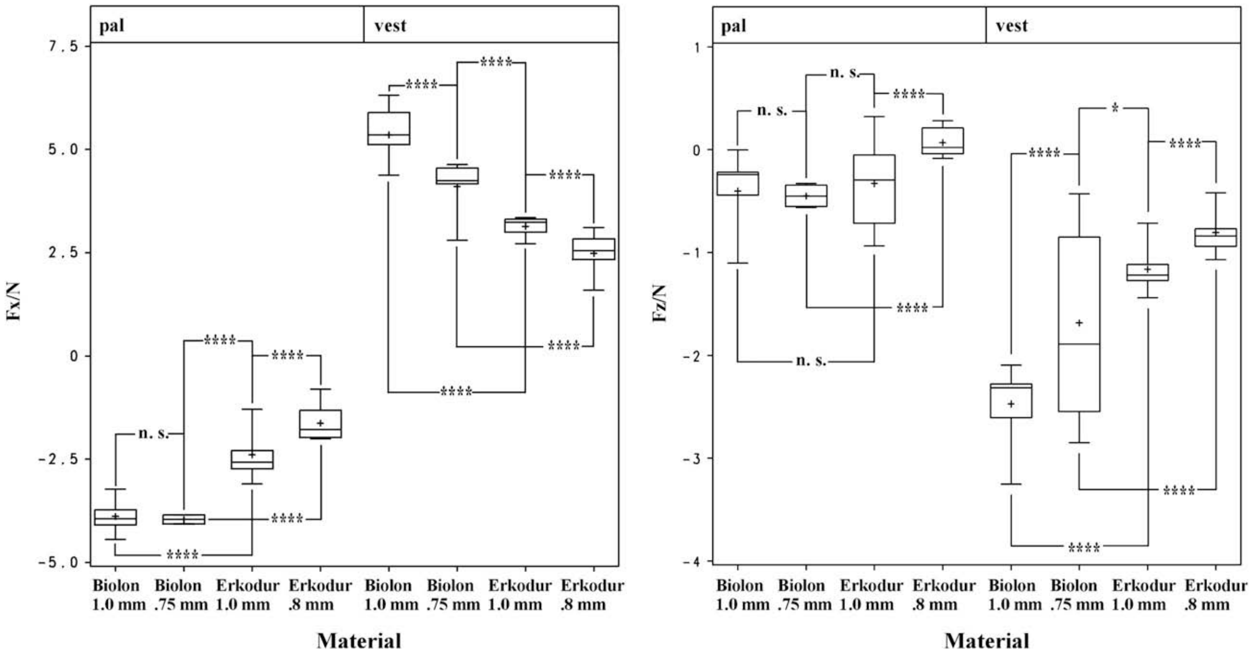

Fig 6. The box plots show comparisons of different levels of force for Fx (*left,* vertical axis) and Fz (*right,* vertical axis) delivered by the particular material (plotted on the horizontal axis of both diagrams) for a displacement range of the incisor edge of –0.151 mm (palatine) and +0.151 mm (vestibular). The plotted forces for Fx are positive for vestibular displacement and negative for palatine displacement of the incisor edge and, in general, are higher than the forces measured for Fz. The forces measured for Fz are close to zero or slightly negative for palatine displacement and generally negative for vestibular displacement of the incisor edge. The negative values for Fz represent intrusive forces for both directions of displacement of the incisor. Levels of significance are indicated by asterisks: $^{*}P \leq 0.05$; $^{****}P \leq 0.0001$. *n.s.*, not significant.

and have thicknesses of 0.762 and 1.016 mm, respectively.[5,10,16] Therefore, we chose those blanks for this investigation.

The measured forces for tipping are approximately 3 to 11 times higher than the ideal forces (0.35-0.60 N) stated by Proffit[17] irrespective of the thickness of the material. Even the forces delivered by the thinner foils are 3 to 8 times too strong.

It was previously demonstrated that the amount of root resorption is directly proportional to the magnitude of force applied, but this is not the case when removable and thermoplastic appliances, in particular, are used.[4,18-20] It is also questionable whether the results of Barbagallo et al[20] regarding root resorption with thermoplastic appliances can be transferred to central incisors, because they are more susceptible to root resorption.[21,22] This aspect needs further research when using thermoplastic appliances for different kinds of tooth movement.

Barbagallo et al[4] measured mean initial forces of 5.12 N at an activation range of 0.5 mm. The material used in that study was an Erkodur 0.8 mm blank. In our study, for that material, force norms between 1.62

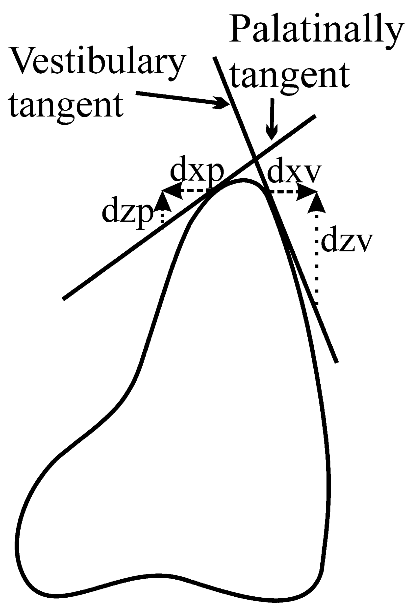

Fig 7. Different inclinations of the vestibular and palatine parts of the thermoplastic appliances near the incisor edge are represented by the 2 tangents. When the incisor edge is displaced in the vestibular and palatine directions over the same distance (|dxv| = |dxp|, *dashed arrow*), the thermoformed appliance must be deformed or lifted along the z-axis much more during vestibular displacement (dzv, *long dotted arrow*) than during palatine displacement (dzp, *short dotted arrow*).

(SD, 0.42) and 2.48 N (SD, 0.48) were measured. These slightly higher forces might be explained by the different morphologies of the crown of a premolar and an incisor and, therefore, the differently located and formed contact areas between the appliance and the tooth.

Apart from the magnitude of the force, the range in which it acts is of greater interest in terms of compression of the PDL and adverse biologic effects. An activation range of ±0.151 mm is adapted to the width of the PDL (0.1-0.3 mm); this diminishes the importance of the force acting initially in horizontal tooth movement.[23,24]

Together with the tipping forces (Fx), the intrusive forces (Fz) could also be measured. This might explain posttherapeutic intrusion, which has been described previously.[25] Altogether, the intrusive forces during vestibular displacement were higher than those for palatine displacement (Fig 6, Table I). A rationale for this might be differences in the vestibular and palatine morphologies of a maxillary central incisor, which tends to result in the geometric dependence of different intrusive forces as shown in Figure 7.

The intrusive forces measured, especially for vestibular displacement, independent of the thickness of the appliance, are overall too high compared with the forces stated by Proffit (0.1-0.2 N).[17] Keeping a low activation range of ±0.151 mm in mind, one could assume that the range in which the intrusive force acts is also small, and, therefore, the amount of force might be irrelevant. Nevertheless, the 2 displacement directions must be considered, as shown in Figure 7. Therefore, it might be possible that, despite a low horizontal activation range, a much higher vertical activation range results.

In this context, it is still unclear how the measured forces are generated. First, they can be explained as reactive forces resulting from local deformation of the appliance at the contact point between the appliance and the tooth. Second, the reduced fit of the appliance produced by the displacement of the tooth might control vertical raising of the appliance near the displaced tooth. But because the appliance is still retained by friction in the molar region, the whole appliance becomes deformed like a bow. This could result in a force acting vertically that tends to press the appliance back on the complete row of teeth again, even at the site of the displaced tooth. This correlates with the observation during this study that, during progressive displacement of the measuring tooth, the appliance lifts up more near the deflected tooth than farther away and deforms progressively. Also, when the deflection of the measuring tooth is reduced again, the appliance tends to reposition itself on the row of teeth. Both mechanisms are concordant with the forces measured in this study, because the different thicknesses of the appliances have a direct influence on the physical properties of the appliance at the contact point and the entire body of the appliance, respectively.

In addition, the vacuum-formed appliances (Erkodur), which also have an additional spacing foil with an initial thickness of 0.05 mm (according to the manufacturer's information) that is removed after thermoforming, delivered lower forces on average than the appliances formed under high pressure (Biolon) (Fig 6, Table I). Potentially, better fitting of the appliances formed under high pressure might increase the friction that reduces the lift-up of the appliance far from the displaced tooth. These findings also support the force-generation theory in relation to reversible deformation of the complete appliance, like a bow, initiated by a local lifting action.

Consequently, one could propose a differentiated therapeutic concept in which just a few teeth in 1 part of the row of teeth are intended to move, and the others provide retention for the appliance. Under these conditions, forces could be generated through local and whole-body deformation of the appliance.

Apart from the different forces measured in vitro due to various thicknesses of the materials, in previous studies, it was shown that material stiffness has no substantial influence on completing therapy or on occlusal improvements or improvements in alignment.[7,8]

Kwon et al[10] used flat probes to measure the forces delivered by a thermoformed appliance. For probes comparable with the thinner blanks we used, we measured forces of 0.522 N (SD, 0.268) for a deflection range of 0.2 mm. In this study, with a corresponding material but at a slightly lower activation range (0.151 mm), the norms of the forces were much higher and were between 1.62 (SD, 0.42) and 4.10 N (SD, 0.62). An explanation for the different measured forces could be that, after thermoforming, the resulting appliance becomes a body that consists of many half shells, crests, sharp bends, and geometric elements that stimulate reinforcement of the material used. This is comparable to the increasing stiffness of paper when it is formed as corrugated cardboard. Therefore, flat probes are not useful for simulating the force delivery characteristics of thermoplastic appliances.

The full clinical significance of our results has yet to be established, and unanswered questions, particularly with regard to the optimal force for tooth movements and complex force delivery characteristics, need to be investigated.

CONCLUSIONS

Removable thermoplastic appliances deliver complex force systems. Despite the tipping force, it was nevertheless possible to show and quantify the intrusive component. The thickness of the blank can influence the force delivered. Another possibility is that the specific thermoforming process, combined with a particular blank, has a significant effect on the magnitude of force associated with a particular appliance.

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