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# Initial forces generated by three types of thermoplastic appliances on an upper central incisor during tipping

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SUMMARY The force properties of thermoformed appliances have not been systematically investigated. Therefore, the aim of the present study was to quantify the forces delivered by thermoplastic appliances manufactured from three different materials, with the same thickness, on a central upper incisor, during tipping.

Five identical appliances were manufactured from three different materials all with a thickness of 1.0 mm (Ideal Clear®, Erkodur®, and Biolon®). For measuring the forces, an isolated measuring tooth, as part of a standardized resin model incorporated in a newly developed measuring device, was tipped in nine $2.\overline{7}$ arc minute ( $0.04\overline{629}$ degree) steps, from 0 to $0.41\overline{6}$ degrees in the vestibular and palatal directions around a rotational axis through the virtual apex, after positioning an 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 determined. Means and standard deviations (SDs) were calculated. The Kruskal–Wallis test for overall effects and the Wilcoxon two-sample test for individual group pairings were used ($P<0.05$ significance level).

The mean *Fx* forces ranged from –2.82 N (SD 0.62) to 5.42 N (SD 0.56). The mean *Fz* forces were between –0.14 N (SD 0.52) and –2.3 N (SD 0.43). The highest intrusive forces were measured during vestibular displacement of the measuring tooth. The forces delivered by the Biolon® appliance were found to be much greater ($P<0.01$) than those of the other materials.

The forces delivered by the materials investigated were mostly higher than those stated in the literature.

## Introduction

The principle of minor tooth movements with thermoplastic appliances was introduced in orthodontics by Kesling (1945). This technique has been advanced by different authors as an alternative or supplement to fixed appliances and also to treat more complex malocclusions (Ponitz, 1971; McNamara *et al.*, 1985; Sheridan *et al.*, 1993; Rinchuse and Rinchuse, 1997; Lindauer and Shoff, 1998; Djeu *et al.*, 2005).

Conventionally, a dental technician manually re-sets the teeth on a plaster model and forms an overlay appliance for each step of tooth movement required. In the commercial Clear Smile® system and for the Essix appliance, manual re-setting of teeth is still common (Sheridan *et al.* 1994; Barbagallo *et al.*, 2008a).

The Invisalign® system was introduced in 1998 (Boyd *et al.*, 2000; Boyd and Vlascalic, 2001). With this system, thermoplastic appliances are constructed on stereolithographic models based on three-dimensional images of individual malocclusions which have been modified using computer programs to produce a series of algorithmic stages.

Although successful treatments with removable thermoplastic appliances have been documented (Wong, 2002; Bollen *et al.*, 2003; Clements *et al.*, 2003; Djeu *et al.*, 2005), the complex force delivery properties of the appliances have not been systematically investigated and only a few studies have been published on this topic (Warunek *et al.*, 1989; Rost *et al.*, 1995; Barbagallo *et al.*, 2008b).

The aim of the present research was to quantify the force components, focussing on the tipping and intrusive forces, exerted by removable thermoplastic appliances produced using three different hard thermoplastic materials, with the same thickness, on a central upper incisor.

## Materials and methods

### *The measuring device*

A device was developed for measuring the forces delivered by orthodontic appliances *in vitro* (Figure 1a). It consists of a quadrangular frame fixed on a base plate by four posts. These units are all made of hard aluminium. A resin bowl

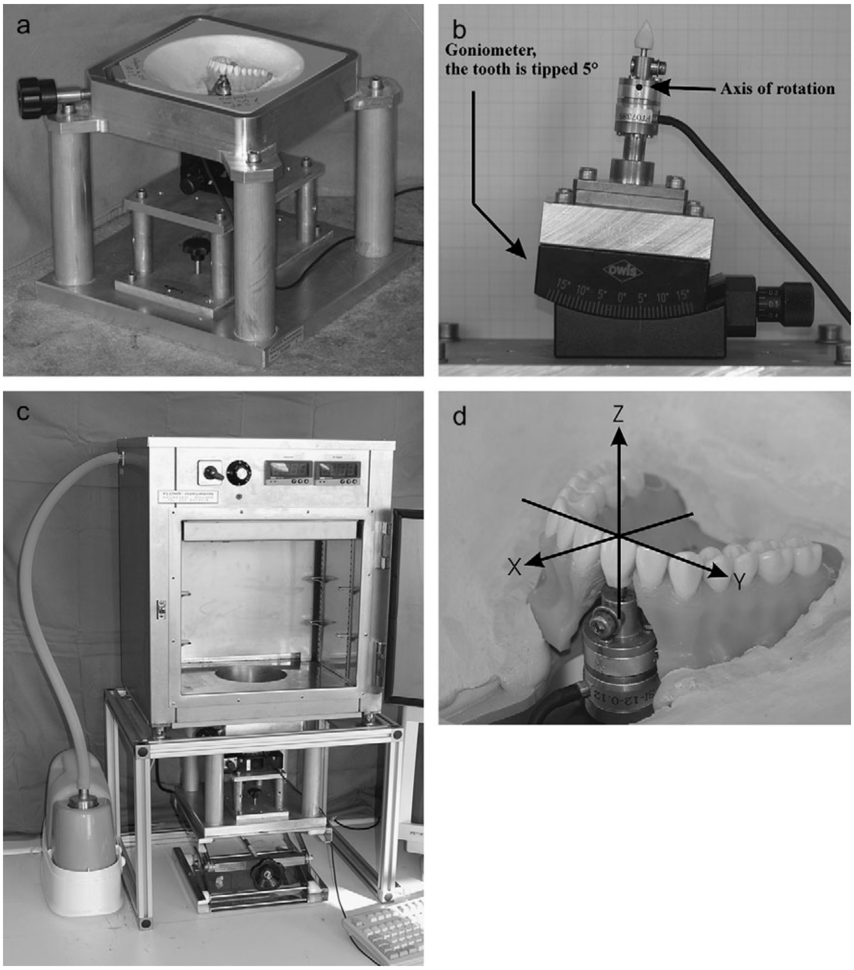


**Figure 1** (a) The resin bowl is fixed in the quadrangular frame with a locking screw. The quadrangular frame, in turn, is fixed by four posts on the base plate. The separated tooth to be measured is fixed on the sensor and aligned in the model, which is fixed in the resin bowl by plaster. The manual positioning system, on which the sensor with the measuring tooth is mounted, is fixed by an aluminium frame on the base plate. Individually arranged configurations of model, tooth, sensor, and positioning system can be combined for every desired tooth and movement direction. (b) The tooth to be measured is tipped 5 degrees in the vestibular direction by the goniometer. The axis of rotation can be found at the calculated virtual apex of this incisor marked by a point. This axis is orientated perpendicular to the image plane. (c) The complete measuring device, which has a hole in its base, is moved by a manual lifting platform into a climate chamber. With this chamber, different temperatures and moisture values can be simulated. (d) The co-ordinate system for the forces and moments measured. The *z*-axis runs through the centre of the incisor edge and the apex. The *x*-axis is orientated perpendicular to the incisor edge and parallel to the direction of motion given by the goniometer.

can be fixed in the frame with a locking screw. In the resin bowl, a standardized resin model (Frasaco GmbH, Tettnang, Germany), with the separated measuring tooth, was fixed by plaster. The measuring tooth itself was fixed on the sensor by a clamp. A plaster key was used for reproducible positioning of the tooth. The sensor was again posted on a manual positioning system used for moving the measuring tooth. For the present study, in order to simulate tipping motion sequences, a goniometer (GO 90-W30, Owis GmbH, Staufen, Germany) was used (Figure 1b).

The manual positioning system, in turn, was fixed by a corresponding aluminium frame on the base plate. The complete measuring device could be moved into a climate chamber to simulate different temperatures and moisture values (Figure 1c).

Individually arranged configurations of the model, tooth, sensor, and positioning system can be combined for every desired tooth and movement direction.

*The sensor*

The sensor used was a Nano 17 (ATI Industrial Automation, Apex, North Carolina, USA), which measures all six components of forces and moments (*Fx*, *Fy*, *Fz*, *Tx*, *Ty*, and *Tz*; Figure 1d). In addition to the power supply, an interface produces an output which can be read by a data acquisition card with a minimum of seven available channels: six for voltage and one for temperature. The data acquisition card reads the signals which are converted to force and torque outputs by ATI DAQ F/T Demo software (version 1.2.4; ATI Industrial Automation) for Windows. This software allows the logging of the current signals in a text file.

For the present study, an individual calibration device from the manufacturer (SI-12-0.12), with 1 per cent full-scale accuracy, was used. This calibration provides sensing values in the optimal measuring range of ±12 N for *Fx* and *Fy*, ±17 N for *Fz*, and ±120 Nmm for *Tx*, *Ty*, and *Tz*, respectively. Using a 16-bit DAQ system, resolutions in the configuration used were ±1/320 N for *Fx*, *Fy*, and *Fz* and ±1/64 Nmm for *Tx*, *Ty*, and *Tz*.

The Nano 17 F/T transducer features hardware temperature compensation to stabilize its sensitivity over a range of approximately ±25°C to room temperatures.

### *Measurements*

Firstly, the measuring tooth was orientated perpendicular with its incisor edge to the direction of motion given by the goniometer. The rotational axis of the measuring tooth was adjusted at the calculated apex. After installation of the measuring device, an impression (Tetrachrom®; Kanidenta, Herford, Germany) of the model with the measuring tooth in a neutral position was obtained and subsequently a plaster model was made 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 15 identical plaster copies were made using Adisil® blue 9:1 (Siladent Dr Böhme & Schöps GmbH, Goslar, Germany). For each material to be evaluated, five appliances extending to the gingival margin were constructed on these models.

The materials and forming machines used were as follows: Ideal Clear® 1.0 mm (Dentsply GAC, Gräfelfing, Germany) with Vacuum Forming Machine 202 (Dentsply GAC), Erkodur® 1.0 mm (Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany) with Erkoform RVE (Erkodent Erich Kopp GmbH), and Biolon® 1.0 mm (Dreve Dentamid GmbH, Unna, Germany) with Drufomat-TE (Dreve Dentamid GmbH).

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 measuring cycle, the forces and moments were set to zero.

For measuring, the tooth was tipped in nine $2.\overline{7}$ arc minute ($0.04\overline{629}$ degree) steps from 0 to $0.41\overline{6}$ degrees in the vestibular and palatal directions around a rotational axis through the calculated apex. The measurements were recorded five times after each step in movement. The angular degrees were converted into movement range in millimetres from the incisor edge.

Depending on the overload protection of the sensor, the incisor edge of the tooth measured could be maximally deflected in most cases up to 0.151 and −0.151 mm. This range is equivalent to the lowest value of an activation range documented in the literature for a clear removable appliance system (Boyd and Vlascalic, 2001).

### *Statistical analysis*

The forces measured at the respective activation range (±0.151 mm) were statistically analysed using SAS® software (SAS Institute Inc., Cary, North Carolina, USA). The force components relevant to orthodontics for tipping and intrusion [*Fx* (horizontal force component/tipping) and *Fz* (vertical force component/intrusion)] were used for further analysis. Means and standard deviations (SDs) were calculated for each material.

The corresponding samples were compared using the Kruskal–Wallis test for overall effects and the Wilcoxon two-sample test for the individual group pairings. When a test against zero was required, a signed-rank test was used.

## Results

Examples of the typical forces and moments measured in the present study as a function of the magnitude of movement of the measuring tooth are shown in Figure 2 for Biolon®. Hysteresis effects were observed, but these were excluded from the present discussion because a maximum deflection of ±0.151 mm, at which hysteresis effects are negligible, was used for inclusion in subsequent analysis. The small variances for each point result from repeated measurements of five appliances, which demonstrate that the influence of the measuring device was negligible. The means and SDs for the forces of relevance for tipping and intrusion at deflections of ±0.151 mm (vestibular and palatal) are given in Table 1 for each material and the corresponding box plots are shown in Figure 3. In all cases, except for *Fz* palatal, Biolon® produced highly significant, stronger forces compared with the other two materials. The differences between Erkodur® and Ideal Clear® were less and the significance of the difference in the forces for the respective materials varied from case to case (Table 2). The values for *Fz* were always highly significantly different from zero, which corresponds to an intrusive force which is stronger in the vestibular displacement direction of the tooth than in the palatal direction (Figure 3).

## Discussion

The measuring device used is comparable to many others described in the orthodontic literature. A general weakness of this type of force measurement is the lack of a simulation of

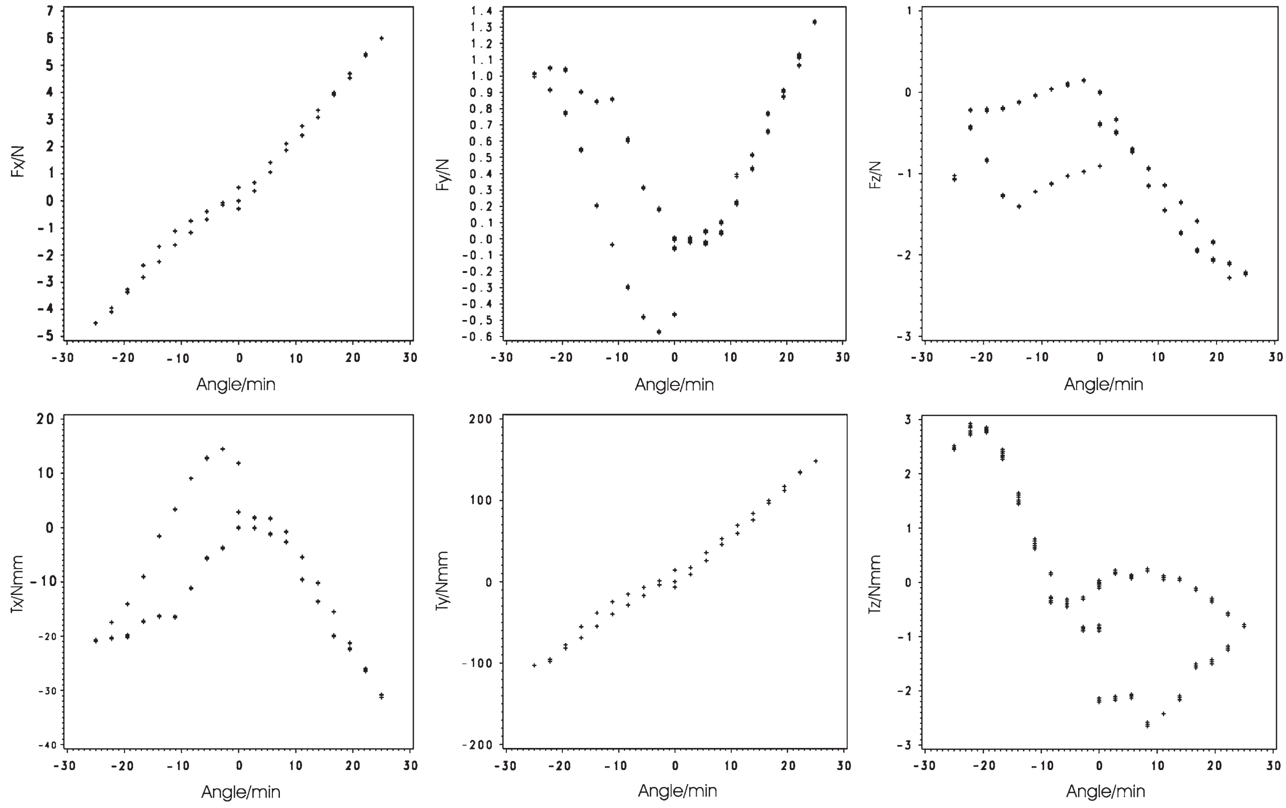


**Figure 2** Typical forces (*Fx*, *Fy*, and *Fz*, upper row) and moments (*Tx*, *Ty*, and *Tz*, lower row) in the present study as a function of the magnitude of displacement of the tooth measured for one material (Biolon®).

**Table 1** Means and standard deviations (SDs) for the variables *Fx* (tipping force along the *x*-axis) and *Fz* (intrusive force along the *z*-axis) in the ranges of deflection of −0.151 and 0.151 mm for the materials used. The varying numbers are a result of the measurements being interrupted below a deflection of ±0.151 mm depending on the overload protection of the sensor.

| Movement range | Material | *n* | Variable | Mean (N) | SD (N) |
|---|---|---|---|---|---|
| −0.151 mm palatal tipping of the measuring tooth | Biolon® | 25 | *Fx* | −3.88 | 0.41 |
| | Biolon® | 25 | *Fz* | −0.4 | 0.38 |
| | Erkodur® | 50 | *Fx* | −2.38 | 0.53 |
| | Erkodur® | 50 | *Fz* | −0.33 | 0.41 |
| | Ideal Clear® | 50 | *Fx* | −2.68 | 0.39 |
| | Ideal Clear® | 50 | *Fz* | −0.44 | 0.45 |
| 0.151 mm vestibular tipping of the measuring tooth | Biolon® | 45 | *Fx* | 5.35 | 0.63 |
| | Biolon® | 45 | *Fz* | −2.47 | 0.34 |
| | Erkodur® | 50 | *Fx* | 3.14 | 0.22 |
| | Erkodur® | 50 | *Fz* | −1.16 | 0.22 |
| | Ideal Clear® | 50 | *Fx* | 3.06 | 0.76 |
| | Ideal Clear® | 50 | *Fz* | −1.03 | 0.25 |

a periodontal ligament (PDL). These circumstances do not allow, for example, determination of the force decay from the measured values as would occur *in vivo* after loading, as a consequence of tooth movement. Hence, this restricts the value of the results as being relevant for initial forces, as they appear immediately after loading when, due to the viscoelastic property of the PDL, no rapid tooth movement can be expected (Synge, 1933; Nakamura *et al.*, 2008).

Unfortunately, due to the complex rheologic and multiphasic properties of a PDL after loading, a clear concept for relating the force system to tooth movement and the reaction of the different parts of the PDL has not yet been presented (Natali *et al.*, 2004; Cattaneo *et al.*, 2008). Nonetheless, the load–deflection characteristics, as shown in Figure 2, give an approximation of the potential force decay in relation to the distance moved by the tooth after loading.

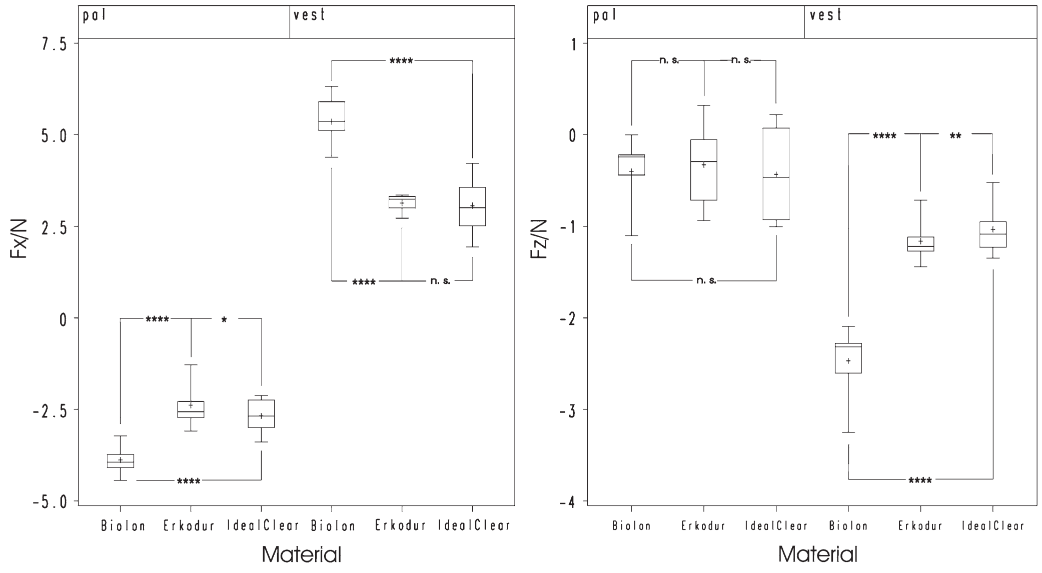


**Figure 3** Box plots showing the different force levels for tipping (*Fx*) and intrusion (*Fz*). $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, and $****P \leq 0.0001$.

**Table 2** Significance levels calculated for comparison of the forces produced by the respective appliances in both displacement directions.

| | Test | Palatal | | Vestibular | |
|---|---|---|---|---|---|
| | | *Fx* | *Fz* | *Fx* | *Fz* |
| Overall | Kruskal–Wallis | $P<0.01$ | $P=0.372$ | $P<0.01$ | $P<0.01$ |
| Biolon versus Erkodur | Wilcoxon two-sample | $P<0.01$ | $P=0.396$ | $P<0.01$ | $P<0.01$ |
| Biolon versus Ideal Clear | Wilcoxon two-sample | $P<0.01$ | $P=0.880$ | $P<0.01$ | $P<0.01$ |
| Erkodur versus Ideal Clear | Wilcoxon two-sample | $P=0.046$ | $P=0.166$ | $P=0.391$ | $P<0.01$ |

When comparing the forces measured with the results in the literature, those in the present study were approximately between half and three-quarters of the force for about one-third of the activation range described by Barbagallo *et al.* (2008b). These differences might be explained by the different diameters of the blanks used (Barbagallo *et al.*, 2008b; Erkodur® 0.8 mm). A further contributing influence could be the different morphologies of the crown of a premolar and an incisor and, therefore, the differently located and differently formed contact areas between the appliance and the tooth. The contact area between the thermoformed appliance and the incisor is located at the incisor edge, where a sharp bend reinforces the appliance, whereas the contact area between the crown of the premolar and the appliance is located nearer to the gingival margin (Barbagallo *et al.*, 2008b), where the appliance is certainly more flexible.

Furthermore, the forces measured for tipping in the present study are approximately 5–11 times higher than the ideal forces (0.35–0.60 N) reported by Proffit (2000). The height of these forces is perhaps relevant for tooth movement velocity and for potential inflammatory root resorption.

In previous studies, comparable high forces for movement of a central upper incisor were applied to evaluate movement velocity (Ren *et al.*, 2003). The results were not uniform but, in some of the tests, higher forces than those reported by Proffit (2000) resulted in increased tooth movement velocity.

In addition, it has been shown that the amount of orthodontically induced inflammatory root resorption is directly correlated with the force magnitude applied (Darendeliler *et al.*, 2004; Harris *et al.*, 2006). Nevertheless, if removable appliances are used, these induce less inflammatory resorption even with higher forces (Linge and Linge, 1983, 1991). This has also been shown recently by Barbagallo *et al.* (2008a) when tipping premolars with thermoplastic appliances.

It is questionable whether these results can be transferred to the tipping of upper central incisors with thermoplastic appliances since upper central incisors are more susceptible to root resorption than all other teeth (Apajalahti and Peltola, 2007; Brezniak and Wasserstein, 2008).

Independent of the height of the forces measured, the range in which they act is of additional interest in relation to

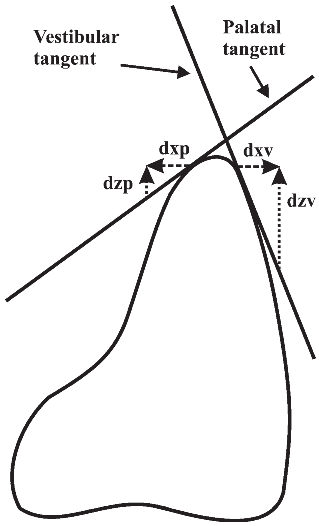


**Figure 4** The different inclinations of the vestibular and palatal parts of the thermoplastic appliances near the incisor edge are indicated by the two tangents. When the incisor edge is displaced in the vestibular and palatal direction for the same distance (|dxv| = |dxp|, dashed arrow), the thermoformed appliance has to be deformed or lifted along the *z*-axis more than during vestibular (dzv = long-dotted arrow) than during palatal (dzp = short-dotted arrow) displacement.

compression of the PDL. If the movement range is adapted to the width of the PDL, it is comparable with any removable appliance possessing an orthodontic screw that usually has an activation range of approximately 0.25 mm for each quarter of a full rotation. In this context, the magnitude of the force becomes relatively irrelevant. Also, if the activation range of a thermoformed appliance increases, the fit of the appliance decreases. Hence, the originally intended amount of deflection cannot act at the particular tooth. This might represent a kind of self-protection mechanism associated with therapy using thermoplastic appliances.

As shown by the present results, an intrusive force, *Fz*, can also be measured together with the tipping force, *Fx* (Table 1). These intrusive forces measured for vestibular displacement of the tooth are overall too high when compared with the forces recommended by Proffit (2000) (0.1–0.2 N). Altogether, the intrusive forces (*Fz*) for the incisor tipped in the vestibular direction were higher than those for the incisor tipped in the palatal direction. An explanation for these results might be the different vestibular and palatal morphologies of an upper central incisor edge (Figure 4, Table 1).

Bearing in mind the low horizontal activation range of ±0.151 mm, it may also be assumed that the range in which the intrusive force acts is very small, and therefore the magnitude of the force may be of minor relevance. Nevertheless, despite the low horizontal activation range in the vestibular direction, a much higher vertical activation range may result, in accordance with the geometric coherence described in Figure 4.

In summary, the measured intrusive forces may be an explanation for post-therapeutic intrusion, as has been previously described (Brezniak, 2008).

In general, two different types of thermoforming procedures can be distinguished: vacuum and high-pressure thermoforming. In general, high-pressure thermoformed appliances deliver significantly higher ($P<0.01$) forces than those produced by vacuum forming (Figure 3, Table 2).

A potential explanation for these observations might be better fitting of the appliances formed with the high-pressure system which potentially leads to higher resistance, as a result of friction, to the forces which act to lift up the appliance. Furthermore, this friction is probably reduced with the Erkodur® appliances which have an additional spacing foil with an initial thickness before thermoforming of 0.05 mm (according to the manufacturer's information) that is removed after thermoforming. This unanswered question will be addressed by further research.

Kwon *et al.* (2008) used flat probes in a three-point bending set-up to measure the forces delivered by thermoplastic appliances. Those authors measured much lower forces for the probes comparable with the blanks used in the present study with a slightly larger activation range. An explanation for these differences could be that, after thermoforming, the used material is reinforced by, for example, half-shells, crests, sharp bends, and other geometric elements. Therefore, flat probes are not useful for simulating the force delivery characteristics of thermoplastic appliances.

## Conclusions

Clear removable thermoplastic appliances generate complex force systems. As well as a tipping force, an intrusive component was also observed in the present study, which may be an explanation for post-therapeutic intrusion after tooth movement with thermoplastic appliances. The measured forces were much higher than stated in the literature as being ideal for tipping movement. The specific thermoforming process in combination with the respective blank has a significant influence on the magnitude of the force of the respective appliance during tipping.

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## References

Apajalahti S, Peltola J S 2007 Apical root resorption after orthodontic treatment—a retrospective study. European Journal of Orthodontics 29: 408–412

Barbagallo L J, Jones A S, Petocz P, Darendeliler M A 2008a Physical properties of root cementum: Part 10. Comparison of the effects of invisible removable thermoplastic appliances with light and heavy orthodontic forces on premolar cementum. A microcomputed-tomography study. American Journal of Orthodontics and Dentofacial Orthopedics 133: 218–227

Barbagallo L J, Shen G, Jones A S, Swain M V, Petocz P, Darendeliler M A 2008b A novel pressure film approach for determining the force imparted by clear removable thermoplastic appliances. Annals of Biomedical Engineering 36: 335–341

Bollen A M, Huang G, King G, Hujoel P, Ma T 2003 Activation time and material stiffness of sequential removable orthodontic appliances. Part 1: Ability to complete treatment. American Journal of Orthodontics and Dentofacial Orthopedics 124: 496–501

Boyd R L, Vlascalic V 2001 Three-dimensional diagnosis and orthodontic treatment of complex malocclusions with the Invisalign appliance. Seminars in Orthodontics 7: 274–293

Boyd R L, Miller R J, Vlascalic V 2000 The Invisalign system in adult orthodontics: mild crowding and space closure cases. Journal of Clinical Orthodontics 34: 203–212

Brezniak N 2008 The clear plastic appliance: a biomechanical point of view. Angle Orthodontist 78: 381–382

Brezniak N, Wasserstein A 2008 Root resorption following treatment with aligners. Angle Orthodontist 78: 1119–1124

Cattaneo P M, Dalstra M, Melsen B 2008 Moment-to-force ratio, center of rotation, and force level: a finite element study predicting their interdependency for simulated orthodontic loading regimens. American Journal of Orthodontics and Dentofacial Orthopedics 133: 681–689

Clements K M, Bollen A M, Huang G, King G, Hujoel P, Ma T 2003 Activation time and material stiffness of sequential removable orthodontic appliances. Part 2: Dental improvements. American Journal of Orthodontics and Dentofacial Orthopedics 124: 502–508

Darendeliler M A *et al.* 2004 Root resorption and its association with alterations in physical properties, mineral contents and resorption craters in human premolars following application of light and heavy controlled orthodontic forces. Orthodontics and Craniofacial Research 7: 79–97

Djeu G, Shelton C, Maganzini A 2005 Outcome assessment of Invisalign and traditional orthodontic treatment compared with the American Board of Orthodontics objective grading system. American Journal of Orthodontics and Dentofacial Orthopedics 128: 292–298

Harris D A, Jones A S, Darendeliler M A 2006 Physical properties of root cementum: part 8. Volumetric analysis of root resorption craters after application of controlled intrusive light and heavy orthodontic forces: a microcomputed tomography scan study. American Journal of Orthodontics and Dentofacial Orthopedics 130: 639–647

Kesling H D 1945 The philosophy of the tooth positioning appliance. American Journal of Orthodontics and Oral Surgery 31: 297–304

Kwon J S, Lee Y K, Lim B S, Lim Y K 2008 Force delivery properties of thermoplastic orthodontic materials. American Journal of Orthodontics and Dentofacial Orthopedics 133: 228–234

Lindauer S J, Shoff R C 1998 Comparison of Essix and Hawley retainers. Journal of Clinical Orthodontics 32: 95–97

Linge B O, Linge L 1983 Apical root resorption in upper anterior teeth. European Journal of Orthodontics 5: 173–183

Linge L, Linge B O 1991 Patient characteristics and treatment variables associated with apical root resorption during orthodontic treatment. American Journal of Orthodontics and Dentofacial Orthopedics 99: 35–43

McNamara J A, Kramer K L, Juenker J P 1985 Invisible retainers. Journal of Clinical Orthodontics 19: 570–578

Nakamura Y *et al.* 2008 Time-lapse observation of rat periodontal ligament during function and tooth movement, using microcomputed tomography. European Journal of Orthodontics 30: 320–326

Natali A, Pavan P, Carniel E, Dorow C 2004 Viscoelastic response of the periodontal ligament: an experimental-numerical analysis. Connective Tissue Research 45: 222–230

Ponitz R J 1971 Invisible retainers. American Journal of Orthodontics 59: 266–272

Proffit W R 2000 Contemporary orthodontics, 3rd edn., C.V. Mosby, Inc, St Louis, p. 304

Ren Y, Maltha J C, Kuijpers-Jagtman A M 2003 Optimum force magnitude for orthodontic tooth movement: a systematic literature review. Angle Orthodontist 73: 86–92

Rinchuse D J, Rinchuse D J 1997 Active tooth movement with Essix-based appliances. Journal of Clinical Orthodontics 31: 109–112

Rost D, Schwarze C W, Hilgers R D 1995 Die Kraftabgabe von Positionern bei unterschiedlicher Schneidezahnprotrusion. Eine In-vitro-Untersuchung. Fortschritte der Kieferorthopädie 56: 104–109

Sheridan J J, LeDoux W, McMinn R 1993 Essix retainers: fabrication and supervision for permanent retention. Journal of Clinical Orthodontics 27: 37–45

Sheridan J J, LeDoux W, McMinn R 1994 Essix appliance: minor tooth movements with divots and windows. Journal of Clinical Orthodontics 28: 659–663

Synge J L 1933 The theory of an incompressible periodontal membrane. The International Journal of Orthodontia and Dentistry for Children 19: 567–573

Warunek S P, Sorensen S E, Cunat J J, Green L J 1989 Physical and mechanical properties of elastomers in orthodontic positioners. American Journal of Orthodontics and Dentofacial Orthopedics 95: 388–400

Wong B H 2002 Invisalign A to Z. American Journal of Orthodontics and Dentofacial Orthopedics 121: 540–541