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# Torquing an upper central incisor with aligners—acting forces and biomechanical principles

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SUMMARY The forces delivered by aligners during torquing have still not been investigated. The purpose of this study was to measure the forces delivered to an upper central incisor during torquing with three different materials of the same thickness, and to describe the biomechanical principles of torquing with aligners.

Five identical appliances were manufactured from each of three materials, all with a thickness of 1.0 mm (Ideal Clear®, Erkodur®, and Biolon®). An upper central incisor, as part of the measuring device, was torqued in defined steps in the vestibular and palatal directions with the respective appliance in place. For statistical analysis, the resulting forces, Fx (forces acting in the palatal and facial directions) and Fz (intrusive force as a side-effect) at a displacement of ±0.15 and ±0.8 mm from the tooth at the gingival margin were calculated.

The mean Fx forces for ±0.15 mm displacement ranged from −1.89 N [standard deviation (SD) 0.48] to 0.11 N (SD 0.1). The mean Fz forces were between −0.97 N (SD 0.57) and −0.07 N (SD 0.22). The highest intrusive forces were measured during palatal displacement of the measuring tooth. An influence of direction of displacement on the levels of force was observed, especially for Fz at the greater displacement of ±0.8 mm.

In relation to the intended amount of root movement during torquing, aligners tend to 'lift up' and therefore no effective force couple can be established for further root control. The force delivery properties are also influenced by the material used and the shape of the tooth.

## Introduction

The principle of moving teeth with appliances such as modern thermoplastic appliances was introduced in orthodontics by Kesling (1945). The advantages and limitations of these types of appliances for correcting different modes of malocclusions have been described by several authors (Boyd and Vlascalic, 2001; Wong, 2002; Bollen *et al.*, 2003; Clements *et al.*, 2003; Djeu *et al.*, 2005; Baldwin *et al.*, 2008; Kravitz *et al.*, 2008, 2009).

In addition to the aforementioned clinical studies which have been documented using removable thermoplastic appliances, the complex force delivery properties of the appliances have also been systematically investigated in two studies of elastic-tooth-positioning devices (Warunek *et al.*, 1989; Rost *et al.*, 1995) and hard plastic materials (Barbagallo *et al.*, 2008b; Hahn *et al.*, 2009a,b). In a recent article, the force- and energy-delivering properties of orthodontic thermoplastic materials were evaluated using flat probes in three-point bending recovery tests (Kwon *et al.*, 2008).

As described in the literature, tipping movement is predictable with thermoplastic appliances, but it remains somewhat difficult to establish a comparable amount of root control (Baldwin *et al.*, 2008; Brezniak, 2008; Boyd, 2003). Another side-effect of tooth movement with thermoplastic appliances is the so-called 'water melon seed' effect, which refers to the unintended intrusion of the tooth moved that is triggered by an intrusive force is caused by distortion of the appliance (Brezniak, 2008).

The aim of the present study was to describe the forces and moments exerted by removable thermoplastic appliances on an upper central incisor during torquing focusing on the forces acting in the vestibular and palatal directions which evoke torquing, and the side-effect of vertical forces acting intrusively. In addition, the differences between three different hard thermoplastic aligners with the same thickness were evaluated in terms of the force delivery properties during torquing.

## Materials and methods

A newly developed modular force–torque measuring device, which has recently been described in detail was used (Hahn *et al.* 2009a,b; Figure 1). It consists of a quadrangular frame fixed on a base plate by four posts. A resin bowl can be fixed in the frame by a locking screw. A standardized resin model (Frasaco GmbH, Tettnang, Germany) with the separated measuring tooth was fixed by plaster in the resin bowl. The measuring tooth itself was reproducibly fixed on the sensor by a clamp. The sensor was again positioned on the manual positioning system used for moving the measuring tooth. The manual positioning system, in turn, was fixed by an aluminium frame on the base plate. The complete measuring device could be moved into a climate chamber to simulate different temperature and moisture conditions.

In order to simulate torquing motion sequences, a goniometer (GO 90-W30; Owis GmbH, Staufen, Germany) was used. This device can torque the tooth around a defined axis, in steps measured in degrees.

A Nano 17 force–torque sensor (ATI Industrial Automation, Apex, North Carolina, USA), which measures all six components of forces and moments (Figure 2) using the individual calibration provided by the manufacturer with 1 per cent full-scale accuracy, was mounted on the goniometer (Figure 1).

After installation of the measuring device, an impression (Tetrachrom®; Kanidenta, Herford, Germany) with the measuring tooth in the neutral position was taken and then a plaster model was made with GC Fujirock® EP (GC Germany GmbH, Munich, Germany). The plaster model was trimmed to a height of 20 mm parallel to the occlusal plane. From this model, 15 identical plaster copies were made, in each case using Adisil® blue 9:1 (Siladent Dr Böhme and Schöps GmbH, Goslar, Germany). For each material evaluated, five appliances were constructed on these models. The appliances always extended to the gingival margin.

The materials, all with a thickness of 1.0 mm, and the forming machines used were: Ideal Clear® (Dentsply GAC, Gräfelfing, Germany) with vacuum-forming Machine 202 (Dentsply GAC), Erkodur® (Erkodent Erich Kopp GmbH, Pfalzgrafenweiler, Germany) with Erkoform RVE (Erkodent Erich Kopp GmbH), and Biolon® (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 forces delivered during torquing, the tooth was tipped in nine 0.416 degree steps from 0 to 5 degrees in the vestibular and palatal directions around a rotational axis through the incisor edge (Figure 3). Angular degrees were converted into movement ranges in millimetres from the region of the gingival margin where the appliance ended. This allowed comparison of the results of the present research with

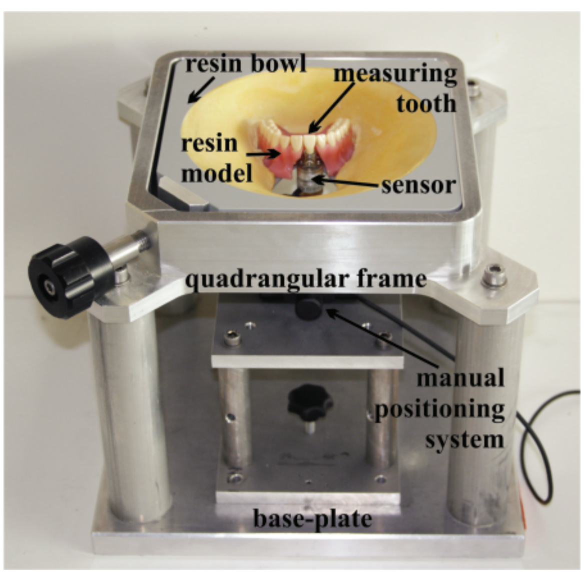


**Figure 1** Basic elements of the measuring device used (modified after Hahn *et al.* 2009a).

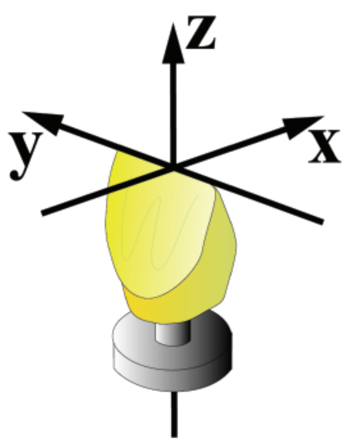


**Figure 2** The co-ordinate system for the forces and moments measured. The z-axis runs through the centre of the incisor edge and the apex. The x-axis is orientated perpendicular to the incisor edge.

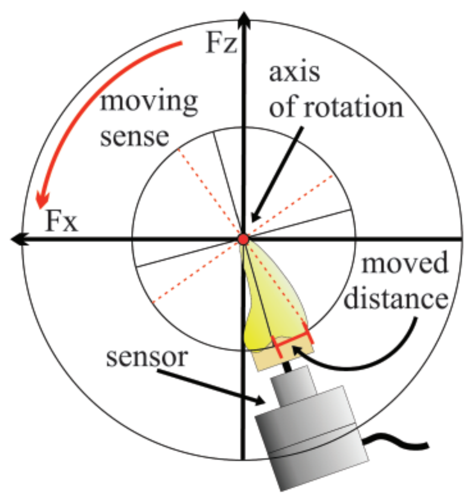


**Figure 3** Schematic diagram of tooth movement. The measuring tooth is orientated perpendicular with its incisor edge and parallel with its centre line to the direction of motion given by the goniometer. The axis of rotation of the measuring tooth was adjusted at the incisor edge for torque motion. In the figure, the axis of rotation is orientated perpendicular to the image plane.

clinical and other biomechanical studies related to this topic. The measurements were recorded five times after each step.

*Statistical analysis*

The forces were analysed statistically using SAS 9.1 software (SAS Institute Inc., Cary, North Carolina, USA). The force components relevant to orthodontics for torquing and intrusion (Fx and Fz) measured in a particular activation range (±0.15 and ±0.8 mm) were used for further analysis. Means and standard deviations (SDs) were calculated for each material at ±0.15 mm (Table 1).

The data were analysed separately for Fx and Fz at a deflection of ±0.15 mm. Since, after visual inspection using histograms and box plots, a Gaussian distribution could not be assumed, the ranks of the observations were used. For overall evaluation, the Kruskal–Wallis test was applied.

The corresponding samples were additionally compared using the Wilcoxon two-sample test (Table 2). For a test against zero, the signed rank test was adopted.

At a deflection of ±0.8 mm during torquing, the means and SDs were also calculated (Table 3), and the absolute values of Fx and Fz were compared using the Wilcoxon two-sample test to evaluate the influences of the two movement directions at a larger deflection range (Table 4).

**Table 1** Means and standard deviations (SD) for the variables Fx (force along the x-axis) and Fz (intrusive force along the z-axis) after torquing movement of the measuring tooth in the ranges of deflection of −0.15 and 0.15 mm for the materials used.

| Movement range | Material | *N* | Variable | Mean (N) | SD (N) |
|---|---|---|---|---|---|
| −0.15 mm palatal displacement of the measuring tooth | Biolon | 25 | Fx | −1.89 | 0.48 |
| | Biolon | 25 | Fz | −0.97 | 0.57 |
| | Erkodur | 25 | Fx | −0.95 | 0.41 |
| | Erkodur | 25 | Fz | −0.56 | 0.61 |
| | Ideal Clear | 25 | Fx | 0.11 | 0.10 |
| | Ideal Clear | 25 | Fz | −0.07 | 0.22 |
| 0.15 mm vestibular displacement of the measuring tooth | Biolon | 25 | Fx | 1.15 | 0.88 |
| | Biolon | 25 | Fz | −0.55 | 0.42 |
| | Erkodur | 25 | Fx | 0.68 | 0.21 |
| | Erkodur | 25 | Fz | −0.38 | 0.36 |
| | Ideal Clear | 25 | Fx | 0.63 | 0.28 |
| | Ideal Clear | 25 | Fz | −0.51 | 0.17 |

## Results

An example of a typical load-deflection diagram (Biolon®, mean values) for Fx (mean) is illustrated in Figure 4 [to facilitate further comparison, the load-deflection diagram for Fx during tipping, taken from previously published data (Hahn *et al.*, 2009b), is also plotted]. Despite the measured Fx forces obtained, the values for Fz were almost highly significantly different from zero, which mainly corresponds to an intrusive force. The mean Fx forces ranged from −1.89 N (SD 0.48) to 0.11 N (SD 0.1). The mean Fz forces were between −0.97 N (SD 0.57) and −0.07 N (SD 0.22). The means and SDs for the forces Fx and Fz at deflections of ±0.15 mm (vestibular and palatal displacement) are given for each material in Table 1. The results of the comparison of the three materials using the Wilcoxon two-sample test are shown in Table 2. The corresponding box plots are given in Figure 5.

In some cases, the vacuum-formed Biolon® appliances produced significantly stronger forces compared with the other two materials. The differences were not statistically significant for all types of movements and were more pronounced for Fx than for Fz (Tables 1–4 and Figures 5 and 6).

A large influence of direction of movement on Fz during torquing was observed. This became increasingly apparent when a larger degree of deflection was evaluated and the absolute values were compared. During a displacement of ±0.8 mm, the absolute values for the Fx forces were mostly in a comparable range for both directions of movement. In contrast, the absolute values for Fz were substantially significantly higher during palatal displacement than during vestibular displacement for all materials (Tables 3 and 4 and Figure 6).

## Discussion

Controlling the torque of an upper central incisor requires the creation of effective couples (Baldwin *et al.*, 2008; Brezniak, 2008): a tipping force, Fx, evoked by reversible deformation of the appliance near the gingival margin and the resulting force in the opposite direction produced by movement of the tooth against the inner opposite surface of the appliance near the incisor edge is necessary. Therefore, a precondition is a close fit of the tooth with its incisor edge in the appliance (Figure 7).

**Table 2** Significance levels calculated for comparison of the forces (Fx and Fz) produced by the respective appliances (Biolon®, Erkodur®, and Ideal Clear®) in both displacement directions (palatal and vestibular) at a deflection of ±0.15 mm.

| | Test | Palatal (−0.15) | | Vestibular (0.15) | |
|---|---|---|---|---|---|
| | | Fx | Fz | Fx | Fz |
| Overall | Kruskal–Wallis | *P* = 0.0392 | *P* = 0.0031 | *P* = 0.6126 | *P* = 0.8106 |
| Biolon versus Erkodur | Wilcoxon two-sample | *P* = 0.0367 | *P* = 0.2963 | *P* = 1 | *P* = 0.8345 |
| Biolon versus Ideal Clear | Wilcoxon two-sample | *P* = 0.0122 | *P* = 0.0122 | *P* = 0.5309 | *P* = 0.8345 |
| Erkodur versus Ideal Clear | Wilcoxon two-sample | *P* = 0.0122 | *P* = 0.2963 | *P* = 0.8345 | *P* = 0.2963 |

**Table 3** Means and standard deviations (SD) for the variables Fx (tipping force along the x-axis) and Fz (intrusive force along the z-axis) after torquing movement of the measuring tooth in the ranges of deflection of −0.8 and 0.8 mm for the materials used.

| Movement range | Material | *N* | Variable | Mean (N) | SD (N) |
|---|---|---|---|---|---|
| −0.8 mm palatal displacement of the measuring tooth | Biolon | 25 | Fx | −6.19 | 1.20 |
| | Biolon | 25 | Fz | −5.57 | 1.16 |
| | Erkodur | 25 | Fx | −5.31 | 0.60 |
| | Erkodur | 25 | Fz | −6.69 | 1.24 |
| | Ideal Clear | 25 | Fx | −2.72 | 0.46 |
| | Ideal Clear | 25 | Fz | −5.49 | 0.61 |
| 0.8 mm vestibular displacement of the measuring tooth | Biolon | 25 | Fx | 4.66 | 1.10 |
| | Biolon | 25 | Fz | −1.32 | 0.69 |
| | Erkodur | 25 | Fx | 4.45 | 0.54 |
| | Erkodur | 25 | Fz | −0.60 | 0.26 |
| | Ideal Clear | 25 | Fx | 5.14 | 0.66 |
| | Ideal Clear | 25 | Fz | −0.69 | 0.20 |

**Table 4** Significance levels calculated for comparison of the absolute forces (Fx and Fz) produced by the respective appliances (Biolon®, Erkodur®, and Ideal Clear®) at a deflection of ±0.8 mm for torquing.

| −0.8 versus 0.8 mm | | Absolute (Fx) | Absolute (Fz) |
|---|---|---|---|
| Biolon | Wilcoxon two-sample | $P = 0.0367$ | $P = 0.0122$ |
| Erkodur | Wilcoxon two-sample | $P = 0.0601$ | $P = 0.0122$ |
| Ideal Clear | Wilcoxon two-sample | $P = 0.0122$ | $P = 0.0122$ |

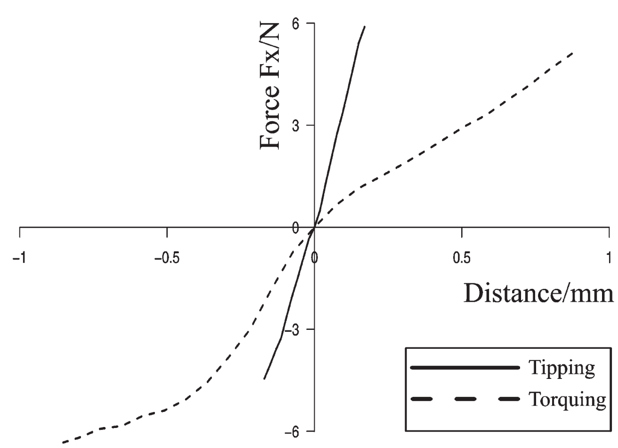


**Figure 4** Typical load–deflection curves for Fx for torquing and tipping illustrated for one material, Biolon®.

Two points which can be deduced from the observations in the present study help to explain the reduced expectation of success for root control with thermoplastic appliances, as described previously (Bollen *et al.*, 2003; Baldwin *et al.*, 2008; Brezniak, 2008).

The greater the amount of root movement planned in one step increments, the less the likelihood that the appliance fits the teeth initially; it will remain, to a certain extent, above the teeth when placed in position. This was observed in the present study even at a deflection of ±0.15 mm and was more pronounced for a deflection of ±0.8 mm during torquing which led to 'lifting up' of the appliance. As a consequence, the incisor edge will not have a close contact with the inner surface of the aligner. In this way, no effective force couple can be produced. Consequently, no root movement but, instead, an initial tipping movement of the tooth in the direction determined by the acting Fx will result (Figures 6 and 7).

In the present measuring set-up, another limitation on torquing an upper central incisor might be the intrusive force, Fz, measured together with the tipping force, Fx (Tables 1 and 2 and Figure 8). During the intended torque movement, the force Fz intrudes the tooth. Consequently, the incisor edge moves away from the inner surface of the appliance, which should act as the counter bearing required for the intended torque movement. Other additive vectors result, which probably do not generate the torque movement originally intended but rather a more pronounced tipping in the Fx direction.

It may be possible that, with minor activation, improved root control might be achieved for an upper central incisor. This is probably not the case for a canine or a premolar because of the totally different crown shape and, therefore, potentially different biomechanical circumstances. In this context, attachments with biomechanically optimized geometric characteristics could be helpful (Bollen *et al.*, 2003; Baldwin *et al.*, 2008; Kravitz *et al.*, 2008).

On the basis of the present results, it was possible to show that crown shape may have a significant influence on the resulting force levels measured, especially for Fz, on the vestibular and palatal sides (Tables 1, 3, and 4). Another indicator regarding this point can be seen in Figure 4. For Fx during torquing, an approximately linear curve progression for increasing vestibular root displacement throughout the whole measured range can be observed. In contrast, the corresponding curve for increasing palatal displacement initially shows a stronger gradient and, after a distance of movement of approximately 0.5 mm, a flattened gradient. A further supporting observation for the influence of the shape of the crown on the forces delivered by a thermoplastic appliance are the differences for Fz between +0.8 and −0.8 mm deflection irrespective of the material used (Figure 6).

A potential rationale for these observations might be provided by the substantial differences between the palatal and vestibular crown shapes. Whereas the vestibular crown shape in a vestibular-oral cross-section can be characterized as a flat convex surface, the palatal crown contour is composed of a more pronounced concave and convex part. In a simplified approach during progressive deflection of the root, the contact areas between the inner surface of the appliance and the crown are changed continuously by slipping along these contour lines. Therefore, the forces on the palatal side are acting at different inclined surface tangents compared with those on the vestibular side, depending on the corresponding amount of tooth displacement

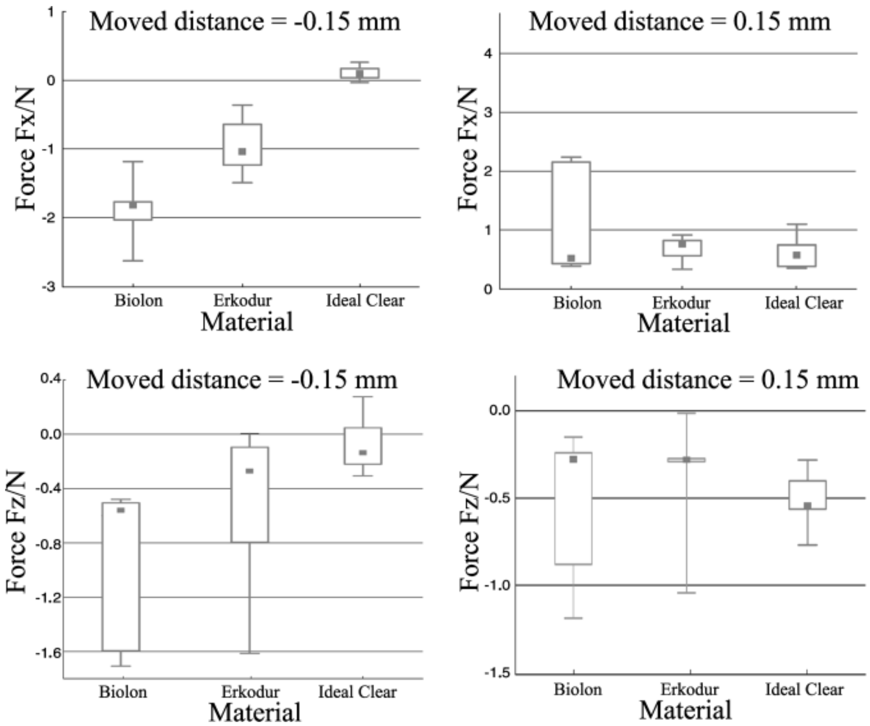


**Figure 5** Box plots showing the force levels for Fx and Fz at a deflection of ±0.15 mm. In each diagram, the respective values are plotted for each material.

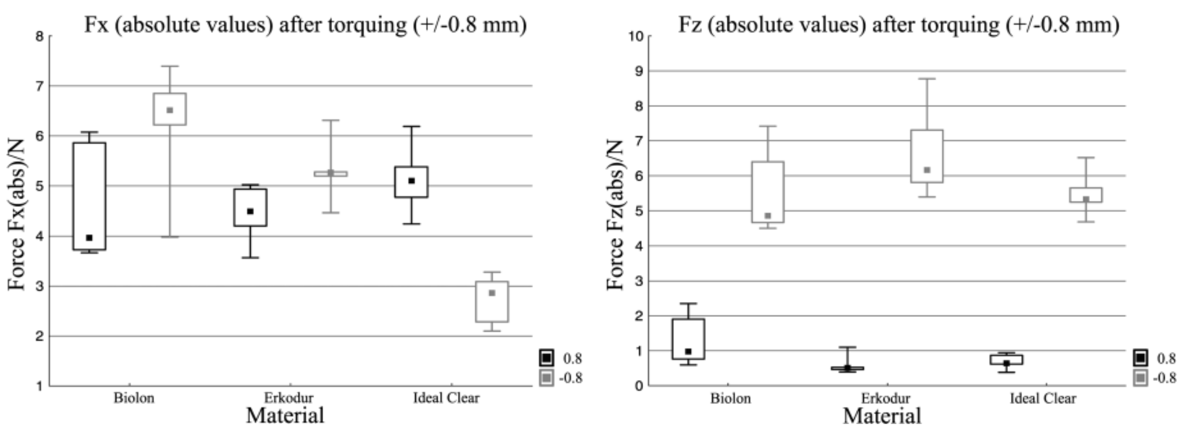


**Figure 6** Box plots showing the force levels (absolute values) for Fx and Fz at a deflection of ±0.8 mm during torquing. In all diagrams, the respective values for palatal (−0.8 mm) and vestibular (+0.8 mm) are combined and plotted separately for each material.

(Figure 8). These findings are supported in the prospective clinical study of Kravitz *et al.* (2009) who reported more accurate lingual (53.1 per cent) than labial (37.6 per cent), crown tip especially for the maxillary incisors.

When comparing the load–deflection curves for Fx of a removable thermoplastic appliance (Biolon®) for tipping and torquing movement (Figure 4), it can be seen that the forces delivered are dependent to a large extent on the type of intended movement. As shown in Figure 4, during tipping a high level of force is reached after a short distance of movement but a comparable force level is achieved during torquing after a longer distance of tooth deflection. This can be explained by the different contact areas between the tooth and the inner surface of the appliance. During tipping of the tooth, such force is mainly generated by deforming the appliance near the incisor edge, where the appliance is reinforced due to a sharp bend. In contrast to tipping, the corresponding forces generated during torquing are mainly caused by bending of the appliance near the gingival margin, where the rigidity of the appliance is reduced compared with the area near the incisor edge. This explains why, during torquing, lower horizontal forces (Fx) are measured than during tipping (for further comparison of the respective measured values refer to Hahn *et al.*, 2009a).

Taken as a whole, the morphology of a particular tooth and the type and amount of intended tooth movement appear to

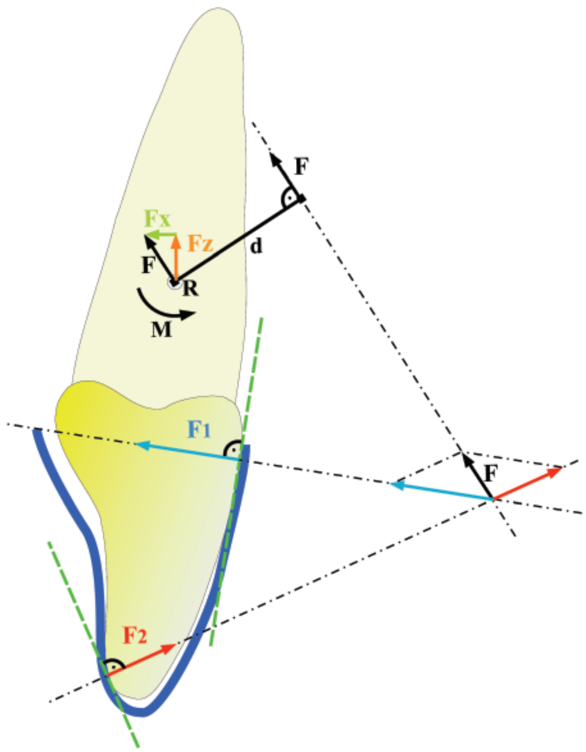


**Figure 7** After positioning the appliance on the tooth, initially the force $F_1$ (Fx measured in the present study) acts. As a consequence, the tooth moves with its incisor edge against the inner palatal surface of the appliance. There, a second force $F_2$ results, which is orientated perpendicular to the surface in contact. While $F_2$ increases, $F_1$ becomes slightly reduced because of the movement. Now, the forces $F_1$ and $F_2$ can be added to the resulting force F by moving them along their lines of action up to the point of intersection, via the parallelogram construction. The resultant force F has a perpendicular distance (d) to the centre of resistance (R). Consequently, a moment of magnitude M = d × F acts on R. The force itself also acts at the centre of resistance. Therefore, the force F along its own line of action is equivalent to a force F acting on R. When deconstructing the force vector F into its components, Fx (horizontally acting force) and Fz (intrusively acting force) result. While the amount of tooth movement by $F_1$ in the present study is estimated to be negligible, the resultant forces Fx and Fz are mainly generated via $F_1$. This is apparent in Figure 8.

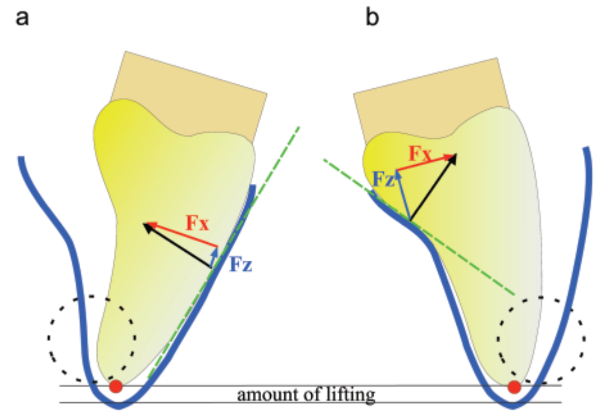


**Figure 8** (a) The root is pre-therapeutically deflected vestibularly with an intended palatal root torque. (b) The reverse situation is shown. In both conditions, the appliance (cross-section/blue line) is bent up near the gingival margin. Because of the reduced fit, the appliance is lifted up. Consequently, the necessary counter bearing near the incisor edge for producing couples to apply a torque to the root is lost (dotted circle). Depending on the various tooth shapes on the vestibular and palatal sides, the resulting forces act on different inclined surface tangents (green dotted lines). Different additive vector quantities result (blue and red arrows).

have a large influence on its contacts with the inner surface of the appliance. This may result in very complex and difficult to predict force couples which, due to tooth movement after positioning the appliance, and therefore continuously changing tooth-to-aligner contact relationships are progressively altered during ongoing therapy. To reduce the problem of crown shape and progressively changing contacts between a moving tooth and the appliance, different aligners with exclusive contacts on modified attachments or selected areas on the crowns might provide a useful solution.

The forces measured during torquing with a deflection of ±0.15 mm tend to be close to the ideal forces stated in the literature (Proffit, 2000). At a deflection of ±0.8 mm, the forces measured were too high especially in the case of the intrusive force, Fz, during palatal displacement of the measuring tooth. The theoretical relevance of these results with regard to biologically adverse effects such as root resorption has been discussed previously (Hahn *et al.*, 2009a,b). The clinical findings however remain controversial (Barbagallo *et al.*, 2008a; Brezniak and Wasserstein, 2008).

The influence of the respective materials on the forces delivered is not unique and it is difficult to describe a clear trend. At the lower activation ranges of ±0.15 mm, the high pressure formed Biolon® appliances tended to deliver higher forces than the other two vacuum-formed materials, but the results were only statistically significant in some cases. This effect has already been described for tipping (Hahn *et al.*, 2009a,b) and could also be observed for torquing in the present study. This result might be explained by the higher friction of the appliance and, in consequence, a larger resistance to lifting up forces which result from progressive deflection of the measuring tooth. These suggestions may be supported by the fact that the Erkodur® appliances, which have an additional spacing foil between the tooth and appliance with an initial thickness of 0.05 mm (according to the manufacturers' information), mainly delivered lower forces than the Biolon® appliances. This foil is thinned out by thermoforming and will in any event be removed afterwards. Therefore, the friction of the appliance might be also reduced. Nevertheless, the differences between the three materials were too heterogeneous to allow a definitive conclusion. Also, the differences measured between the three materials evaluated do not seem to have an influence on the biomechanical behaviour of the aligners.

The forces delivered by any orthodontic appliance on a tooth are not the only factor relevant for tooth movement and biological side-effects. It is important to take into consideration local stresses and strains, which are experienced by the cells within the supporting tissues (Mitchell *et al.*, 1973; Roberts *et al.*, 1981; Yoshikawa, 1981). To-date, direct measurement of these values has been difficult and a reliable biomechanical model for their derivation has not been presented in the literature. Moreover, it is also almost impossible to simulate the periodontal tissues in an *in vitro* set-up (Natali *et al.*, 2004; Ren *et al.*, 2004; Cattaneo *et al.*, 2008). That is why *in vitro* research on the release of force by different appliances used in orthodontics has mainly been limited to an experimental set-up such as that used in the present study, with a rigid connection between the particular measuring tooth and the sensor. With this set-up, for example, periodontal ligaments and alveolar bones cannot be simulated.

The value of the forces measured with the present measuring device is thus of relevance to the situation immediately after loading when, due to the visco-elastic properties of the periodontal ligament, no pronounced rapid tooth movement can be expected (Synge, 1933; Nakamura *et al.*, 2008).

## Conclusions

In addition to the required force, Fx, an intrusive force, Fz, could be measured that alters the possibility of torquing roots with aligners. The forces and couples delivered by aligners are determined by the shape of the crown and the type and amount of displacement of the particular tooth and, therefore, the contacts between the particular tooth and the inner surface of the appliance. The predictability of the corresponding movement sequence is thereby reduced. The differences between the three materials measured were too heterogeneous to allow a definitive conclusion.

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