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 2.7 arc minute (0.04629 degree) steps, from 0 to 0.416 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 $F_x$ (tipping) and $F_z$ (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 $F_x$ forces ranged from −2.82 N (SD 0.62) to 5.42 N (SD 0.56). The mean $F_z$ 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
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 ($F_x$, $F_y$, $F_z$, $T_x$, $T_y$, and $T_z$; 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 approximately ±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, appliances extending to the gingival margin were constructed 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...
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.

Table 1. Means and standard deviations (SDs) for the variables $F_x$ (tipping force along the $x$-axis) and $F_z$ (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.

<table>
<thead>
<tr>
<th>Movement range</th>
<th>Material</th>
<th>$n$</th>
<th>Variable</th>
<th>Mean (N)</th>
<th>SD (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-0.151$ mm palatal tipping of the measuring tooth</td>
<td>Biolon®</td>
<td>25</td>
<td>$F_x$</td>
<td>$-3.88$</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Biolon®</td>
<td>25</td>
<td>$F_z$</td>
<td>$-0.4$</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>Erkodur®</td>
<td>50</td>
<td>$F_x$</td>
<td>$-2.38$</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Erkodur®</td>
<td>50</td>
<td>$F_z$</td>
<td>$-0.33$</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Ideal Clear®</td>
<td>50</td>
<td>$F_x$</td>
<td>$-2.68$</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>Ideal Clear®</td>
<td>50</td>
<td>$F_z$</td>
<td>$-0.44$</td>
<td>0.45</td>
</tr>
<tr>
<td>$0.151$ mm vestibular tipping of the measuring tooth</td>
<td>Biolon®</td>
<td>45</td>
<td>$F_x$</td>
<td>$5.35$</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>Biolon®</td>
<td>45</td>
<td>$F_z$</td>
<td>$-2.47$</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Erkodur®</td>
<td>50</td>
<td>$F_x$</td>
<td>$3.14$</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Erkodur®</td>
<td>50</td>
<td>$F_z$</td>
<td>$-1.16$</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>Ideal Clear®</td>
<td>50</td>
<td>$F_x$</td>
<td>$3.06$</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Ideal Clear®</td>
<td>50</td>
<td>$F_z$</td>
<td>$-1.03$</td>
<td>0.25</td>
</tr>
</tbody>
</table>
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
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, $F_z$, can
also be measured together with the tipping force, $F_x$ (Table 1).
These intrusive forces measured for vestibular displace-
ment 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 ($F_z$) 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 pro-
ducts can be distinguished: vacuum and high-pressure ther-
moforming. In general, high-pressure thermoformed appli-
cances 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 ques-
tion 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 meas-
ured forces were much higher than stated in the literature as
being ideal for tipping movement. The specific thermo-
forming 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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