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In vivo determination of the centres of resistance of maxillary anterior teeth subjected to retraction forces

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SUMMARY *This study was designed to locate the centres of resistance of consolidated units of two, four, and six anterior teeth during retraction in two human subjects. Initial displacements of these units were separately measured when retraction forces were applied at different levels by means of a device for displacement measurement using magnetic sensors and magnets. By calculating the angle of rotation from the displacements measured, the location of the centre of resistance was determined for each unit.*

The results showed that the centres of resistance of the two- and four-incisor units were approximately at the same position, whilst that of the six-tooth unit was observed to be more incisal. Clinically, this finding indicates that translation can be achieved with a smaller amount of moment-to-force ratio in en masse *retraction than in two- or four-incisor retraction. The results also indicate that the location of the centre of resistance of the anterior segment during retraction may depend on the palatal alveolar bone height, rather than on the labial alveolar bone height.*

Introduction

Efficient orthodontic tooth movements largely depend on an appreciation of the relationship between a line of action of the force and the centre of resistance of a tooth. A single force passing through the centre of resistance results in bodily tooth movement. On the other hand, a force not acting through the centre of resistance produces a moment that tends to rotate the tooth. The magnitude of a moment is represented by the product of the force magnitude, and the perpendicular distance between the line of the force and the centre of resistance. The longer the moment arm, the greater the rotating effect. These biomechanical principles are helpful in achieving predictable and controlled tooth movement.

Maxillary four incisor retraction, or *en masse* retraction of the anterior segment including canine teeth, is used in the treatment of extraction and/or maxillary protrusion cases. Knowledge concerning the locations of the centres of resistance of various units of maxillary anterior teeth would contribute to a successful treatment result and possibly a reduction in treatment time. Although many investigations (Davidian, 1971; Nikolai, 1974; Burstone and Pryputniewicz, 1980; Dermaut *et al*., 1986; Tanne *et al*., 1988; Pedersen *et al*., 1991a; Vollmer *et al*., 1999; Choy *et al*., 2000) have been carried out to determine the centre of resistance of a single tooth, it still seems much more difficult to estimate that of a complex of teeth analytically or experimentally. Several attempts have been made to locate the centre of resistance of various units of the anterior segment experimentally on human skulls; nevertheless, these experiments had some disadvantages. The mechanical properties of the periodontal ligament (PDL) may have changed considerably on human autopsy materials (Pedersen *et al*., 1991b) or the PDL has been completely replaced by a synthetic substance with similar characteristics when using dry skulls (Van den Bulcke *et al*., 1986, 1987). Since results obtained from autopsy material and dry skulls are inconsistent and confusing, they cannot be applied directly to orthodontic treatment planning. Such problems can be eliminated by placing magnetic sensors and magnets in the oral cavity for measuring tooth displacements *in vivo*.

The purpose of this study was to determine the locations of the centres of resistance of consolidated units of two, four, and six anterior teeth during retraction in human subjects using a magnetic sensing system for tooth displacement.

Materials and methods

A magnetic sensing system for measuring initial tooth displacement and estimating the location of the centre of resistance under orthodontic force has been developed and demonstrated as an accurate method (Yoshida *et al.*, 1995, 2000). An experimental set-up mounted on a plaster model is shown in Figures 1 and 2. The main part of the system comprises 16 magnetic sensors and two magnets. To measure three-dimensional displacement of a tooth, eight magnetic sensors are arranged in a cubic array around a magnet and mounted on an aluminium channel. In the oral cavity, the magnets are attached to the anterior teeth and the sensors to the posterior teeth. One sensor unit is placed palatal to the maxillary anterior teeth and cemented to the posterior teeth by a resin splint. The other sensor unit extends labially to the anterior segment by an aluminium plate from the splint. Two magnets are placed in the centre of each sensor unit. To connect the magnets to the incisors, aluminium rods are placed between them as an extension and bonded with 4-META resin (Super-Bond, Sun Medical Co., Kyoto, Japan). The apparatus attached to the incisors is constructed from lightweight material, which is in total less than 8 g in weight, in order to minimize the effect of its dead load on tooth displacement. Displacements of the two magnets are detected by the sensors in real time and analysed for the trajectories of the anterior segment subjected to orthodontic forces. The system is designed to achieve a displacement resolution of 1 μm. The mean percentage of measurement errors was determined to be less than 1 per cent in the working area of 600 cubic micrometres from an extra-oral calibration.

Lingually-directed forces were applied to the anterior segment at different levels to simulate the clinical situation in which anterior retraction is performed. A crown for embracing a maxillary central incisor was cast in titanium. A titanium angle with five hemispherical notches drilled into the surface was used for an indication of the location of force application (Figure 1). The angle was welded to the titanium crown, which was to be cemented to the central incisor, so that the labial surface with the five notches as guides for force application could be positioned perpendicular to the occlusal plane. Level 1 of retraction force was located at a point 8.5 mm

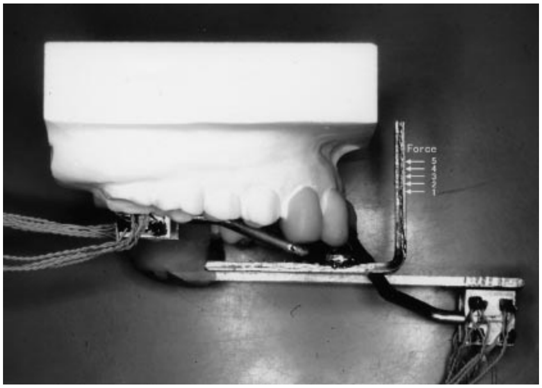

Figure 1 Sagittal view of the experimental set-up. The five points of force application to the titanium angle are illustrated.

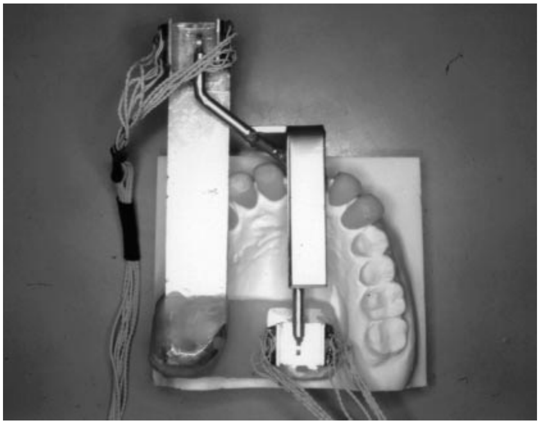

Figure 2 Occlusal view of the experimental set-up. Sensor units were placed labially and palatally to the anterior segment. Crowns were separately fabricated to hold each tooth in the anterior segment.

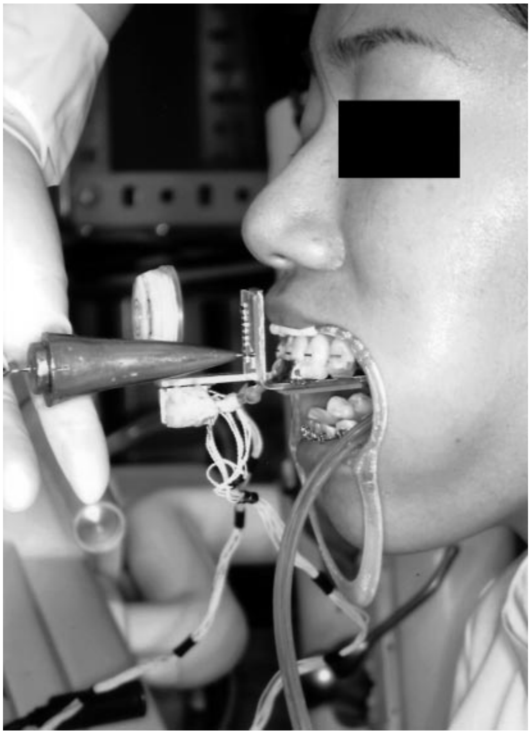

Figure 3 Force application and measurement.

apical to the incisal edge of the central incisor. Four more points were set at 2-mm intervals perpendicular to the occlusal plane toward the apex of the root. Resin crowns were separately fabricated to hold the other anterior teeth. The crowns were consolidated in units of two, four, or six teeth with 4-META resin, and forces of 1, 2, and 3 N were applied to the units of two, four, and six anterior teeth, respectively, so that 0.5 N of the force could be distributed to each tooth. The forces were delivered by applying lead weights perpendicularly to the titanium angle extending from the tooth while the subjects were lying horizontally. The labial surface of the angle was checked for parallelism with the ground using a levelling instrument attached to the angle in order to maintain the direction of the force constant during measurement (Figure 3).

The subjects consisted of two adult females who were undergoing orthodontic treatment after a diagnosis of maxillary protrusion. Following maxillary first premolar extractions, six measurements were performed and averaged.

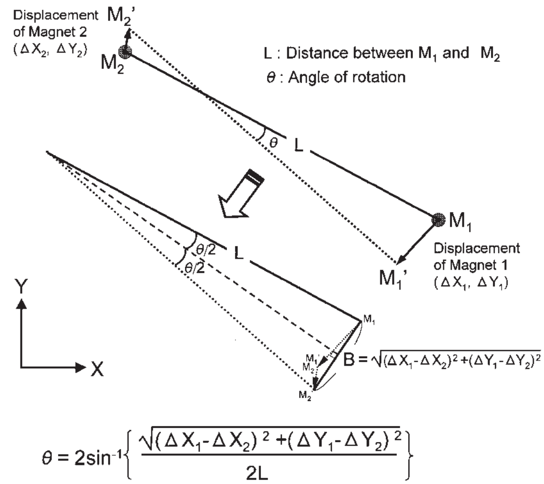

Figure 4 Calculation of the angle of tooth rotation in the sagittal plane from displacements of the two magnets.

The angle of rotation of the anterior teeth in the sagittal plane was calculated from displacements of the two magnets as shown in Figure 4. Points M_1 and M_2 indicate the positions of the two magnets before, and M_1' and M_2' after displacement. When a line M_1' M_2' is translated with a point M_2' falling on a point M_2, an isosceles triangle is formed, whose vertical angle, equal sides, and base are θ, L, and B, respectively. Therefore, the angle of tooth rotation θ is expressed as a trigonometric function of displacements of the two magnets and L. The graphs were made by plotting the angle of tooth rotation against the level of force application. The level of force application at which no rotation occurred was then determined and considered to be the line on which the centre of resistance lay.

Results

Figure 5 shows the angle of tooth rotation as a function of the level of force application, and demonstrates the geometric relationship of the lines passing through the centre of resistance of the three dental units to the maxillary anterior segment and the surrounding alveolar bone for each of the subjects. A positive sign indicates lingual crown tipping and a negative sign labial

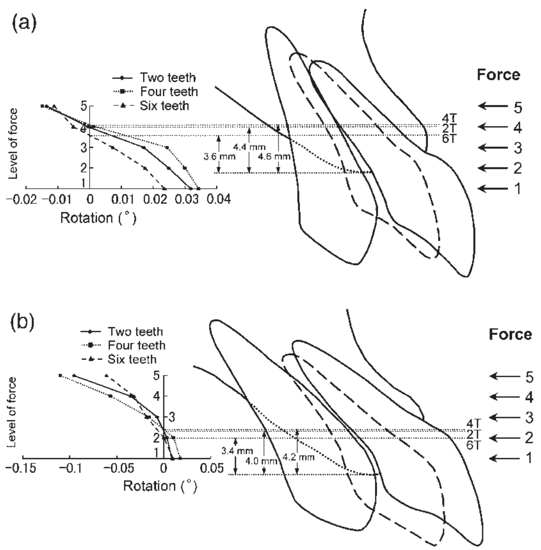

Figure 5 Graph representing the angle of tooth rotation as a function of the level of force application and geometric relations of the centre of resistance of each dental unit to the anterior segment and the surrounding alveolar bone for each of the subjects. (a) Subject 1; (b) subject 2.

crown tipping. The direction of tooth rotation was observed to change from lingual to labial crown tipping when the level of force was moved apically.

The centre of resistance was located at the level where the force produced zero rotation, namely, the intersection of the line representing the angle of tooth rotation and *y* axis on the graph (Figure 5). For subject 1, the centres of resistance were located at level 4 for the two-incisor unit and just above level 4 for the four-incisor unit. For the unit of six teeth, the centre of resistance was located at levels 3–4. The location of the centre of resistance of the six-tooth unit was significantly incisal to that of the two- or four-incisor units.

Likewise, the centres of resistance were observed at levels 2–3 for the two- and four-incisor units, and at level 2 for the six-tooth unit for subject 2. That is, the locations of the centre of resistance of the two- and four-incisor units were almost the same, and that of the six-tooth unit was more incisal.

In order to investigate the geometric relationship of the centre of resistance of each anterior unit to the anterior segment and the surrounding alveolar bone, the perpendicular distances from the horizontal line indicating the level of the marginal bone to the line, on which the centre of resistance exists, were measured on the lateral cephalogram of each of the subjects (Figure 5). For subject 1, the centres of resistance of the two-, four-, and six-tooth units were located 4.4, 4.6, and 3.6 mm apical to the height of the palatal bone level, respectively, and 4.0, 4.2, and 3.4 mm in the same order for subject 2. Although the centres of resistance were located apical from the labial bone level for subject 1, they were observed on the opposite side, namely, incisally from the labial bone level for subject 2.

Discussion

Data on the locations of the centre of resistance for various units of the anterior segment obtained from the present and previous studies are summarized in Table 1. The coefficients of variation of the values for six measurements were less than 8.2 per cent. The reproducibility of the measurements was, therefore, considered to be acceptable. A similar tendency was observed between the subjects and, although only two subjects were employed due to practical difficulties of *in vivo* measurement, the results are thought to be reliable.

The present investigation shows that the location of the centre of resistance of the two-incisor unit is slightly incisal in relation to that of the four-incisor unit. Since the difference in locations of these two units is only 0.2 mm for

Table 1 Data on the locations of the centre of resistance.

Tooth-unit	Distance from the incisal edge to the centre of resistance (mm)			
	1	2	3	4
2T	14.5	11.1	10.7	10.3
4T	14.7	11.3	12.3	8.1
6T	13.7	10.5	13.7	10.6

1, Present study (subject 1). 2, Present study (subject 2). 3, Van den Bulcke *et al.* (1987). 4, Pedersen *et al.* (1991b).

both of the subjects, its effect on the type of tooth movement is not considered to be clinically significant. The centre of resistance of the six-tooth unit was found to be significantly incisal compared with those of the two- and four-incisor units for both subjects. That is, the inclusion of the canines in the anterior segment moved the centre of resistance incisally by between 0.8 and 1.0 mm. This suggests that almost the same value of moment-to-force ratio is required for translation when two or four incisors are retracted. In *en masse* retraction, translation can be achieved with a smaller amount of moment-to-force ratio than in two- or four-incisor retraction.

This finding is in contradiction to the results obtained from *in vitro* measurements (Van den Bulcke *et al*., 1987; Pedersen *et al*., 1991b) and a theoretical analysis (Melsen *et al*., 1990). Van den Bulcke *et al*. (1987) reported that the location of the centre of resistance shifted apically as the number of teeth in the anterior unit increased in the order two, four, six, based on laser holographic measurements using human dry skulls. Pedersen *et al*. (1991b) found that the centre of resistance was located at almost the same position for the two- and six-tooth units, but more incisally for the four-tooth unit using a strain gauge technique on a human autopsy material. Melsen *et al*. (1990) theoretically estimated the location of the centre of resistance of a six-tooth unit as the average position of the centroid of each tooth. Consequently, its location was found halfway between the midpoint of the four-incisor unit's centres of resistance and the canines' centre of resistance. They all concluded that canines with long roots have a considerable effect in moving the centre of resistance of the anterior segment apically.

Disagreement between *in vivo* and *in vitro* studies may mainly be due to the difference in the characteristics of the periodontal tissues. Since the mechanical properties of the PDL are considered to be substantially changed on human autopsy material, and a substitutional material was used to simulate the PDL when using dry skulls in the previous *in vitro* studies, measured tooth displacements might not reflect physical distortion of the periodontium under normal conditions. A theoretical determination of the centre of resistance of the anterior segment including canines also seems more difficult, since its location is considerably influenced by the size, shape, and position of the canines (Van den Bulcke *et al*., 1987). The present *in vivo* study shows that the centre of resistance of the six-tooth unit cannot be simply represented as the average position of the centroid of each tooth in the sagittal plane.

It has been proposed that when the anterior segment of six teeth tip as a consolidated unit, the initial centre of rotation is near the apices of the incisors (Burstone, 1982). This indicates that the apices of canines are depressed into their sockets at the same time; therefore, the adjacent bone is highly stressed and may strongly resist the tipping action. As a result, the centre of resistance is thought to shift incisally as the number of teeth in a unit increases from two or four to six.

In the strictest sense, the present experiment was not carried out in a real clinical situation. First, the retraction of the anterior segment is commonly performed with activating closing loops incorporated into a rectangular wire, or by sliding a straight rectangular wire distally through brackets and tubes. In this situation, consolidation of the anterior segment is not completely rigid, since the arch wire has flexibility. On the other hand, the crowns were individually fabricated to hold each of the anterior teeth and were firmly consolidated in a unit using 4-META resin in this experiment. Such an arrangement may prevent the anterior segment from tipping, thereby causing the location of the centre of resistance to move somewhat incisally. Secondly, the four incisors are normally retracted after canine retraction. However, all measurements were made before canine retraction. The contact between the incisors and the canines may also reduce the tipping tendency, namely, the location of the centre of resistance of the four incisors seems to displace slightly to the incisal direction. An experimental set-up should be more closely approximated to clinical situations in future studies.

There was a large difference between the subjects in the location of the centre of resistance of each unit. This may be due to the variation of the marginal bone level on the palatal, rather than that on the labial side, since the distances from the incisal edge to the labial alveolar crest measured on a line perpendicular to the retraction force were nearly the same between the subjects. In contrast, there was a great variation in the distance from the incisal edge to the palatal alveolar crest. In other words, the location of the centre of resistance perhaps depends on the palatal alveolar bone height and not on the labial alveolar bone height during anterior tooth retraction. In fact, there was only a small difference between the subjects in the perpendicular distance from the palatal bone level to the centre of resistance of each unit. The centre of resistance of the two- and four-incisor unit was located 4.3 ± 0.3 mm apical to the palatal bone level, and that of the six-tooth unit was approximately 0.8 mm more incisal (Figure 5). This indicates that the palatal bone level may be an indicator of the location of the centre of resistance of the anterior segment. It is considered that in cases of reduced palatal alveolar bone height such as in subject 1, the centre of resistance is located at a more apical position.

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