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The value of the centre of rotation in initial and longitudinal tooth and bone displacement

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SUMMARY Force application on teeth and bone structures results in orthodontic and orthopaedic movements. The effect of force application during different time intervals (initial and longitudinal displacements) can be evaluated by describing the displacement vectors or by constructing the centres of rotation of the displacements.

The aim of this investigation was to review different experimental studies to compare the position of the centre of rotation (CR) with the displacement vectors of the object (tooth or bone) after force application. The results indicate that the measuring procedure and the use of the CR to describe the displacement are very sensitive: a large discrepancy in the position of the CR does not necessarily lead to a major change in the displacement vector of the object.

Displacement vectors seem to be more appropriate in describing both initial and longitudinal tooth or bone displacements.

Introduction

General considerations

In a series of experiments carried out at the Department of Orthodontics, University of Ghent, the value of the skull as a predictor for orthodontic and orthopaedic displacement was investigated (Dermaut and Beerden, 1981; Kleutghen *et al.*, 1982; Dermaut *et al.*, 1986; De Clerck, 1987; De Clerck *et al.*, 1990; Govaert and Dermaut, 1997; De Pauw *et al.*, 1999a,b; Billiet *et al.*, 2001). The purpose of these studies was to test the hypothesis as to whether the initial displacement of a model can be considered as a predictor for longitudinal displacement. The initial displacements after force application are very small and can be measured *in vitro* as well as *in vivo*. Different *in vitro* models have been described in an attempt to understand the biomechanics and the influence of force application on dental and skeletal units. Initial displacements can be a forecast for the longitudinal or secondary displacement *in vivo* after force application. These 'longitudinal' orthopaedic changes or 'secondary' displacements represent the biological response of bone or teeth to the force application after a period of time. The relationship between the initially measured displacements and the secondary effects was a second hypothesis tested (De Pauw *et al.*, 1999b; Soenen *et al.*, 1999).

Treatment effects and changes due to normal growth are often measured on cephalograms using displacement vectors. There are two ways to describe displacement of an object. Both the displacement vector of any point of an object, as well as the centre of rotation (CR) around which it rotates, can be measured initially and longitudinally. To evaluate initial displacements after force application, the initial CR might be used (Christiansen and Burstone, 1969; Burstone and Pryputniewicz, 1980; Goldin *et al.*, 1980; Pryputniewicz *et al.*, 1980). To describe longitudinal displacements, the CR around which bone structures or teeth rotate has also been used (Worms *et al.*, 1973; Hurd and Nikolai, 1976; Nanda, 1978; Hocevar, 1981; Rune *et al.*, 1982, 1983).

In both applications (initial and longitudinal displacements), the CR is constructed starting from the displacement vectors (Hocevar, 1981; Smith and Burstone, 1984). Depending upon the orthodontic or orthopaedic displacement, a positional change in the CR might occur at different time intervals.

According to previous experience, the location of the CR is a very sensitive measuring procedure. Moreover, an important standard deviation has been observed after repeated measurements.

From the bases of experiments performed earlier, a comparison will be made between the value of the location of the CR and the displacement vectors of the object (tooth or bone).

Definitions

Displacement vectors. When a point of an object is displaced over a certain distance (i.e. due to an orthopaedic or orthodontic force system), the vector connecting both positions is defined as 'the displacement vector'. It has a direction, a length, and a sense.

CR. The CR can be defined as the point around which the tooth or bone seems to rotate during a period of time. The CR of a movement can be obtained by construction of the mid-perpendicular lines on the displacement vector for each point under study. The intersection of these perpendicular lines is defined as the CR (Figure 1). The beginning and final positions of any two points of a displaced object are sufficient to construct the CR. The displacement of other points of the same object can be calculated by applying the formula shown in Figure 1:

$$d = 2r \sin \theta/2$$

$$r = a/(\cos \theta/2)$$

$$d \text{ arc} = 2\pi r\theta/360$$

where d (displacement of one point of the object) = cord; r = distance of the measured point to the CR; θ = the angle of the rotation (degrees); a = mid-perpendicular on the displacement vector.

Initial displacement. Initial or primary bone and tooth displacements are the immediate displacements after a force application on the bone or a tooth. Initial displacement is the immediate result of the resistance of bone or teeth to different force application systems in which the biological parameters are left constant by using the same skull. Conversely, in clinical studies the effect of tooth or bone displacement can be measured in different patients inducing individual biological variability as a cause factor for different reactions to the same force application. Moreover, by measuring initial displacements, the differential reaction of bone or teeth can be evaluated immediately after force application. These initial displacements are very small and can be measured by means of laser measuring techniques. Double exposure holography and speckle interferometry are non-invasive techniques which can be used to describe bone or tooth displacement after force application (Burstone and Pryputniewicz, 1980; Goldin *et al.*, 1980; Pryputniewicz *et al.*, 1980; Dermaut and Beerden, 1981; Kleutghen *et al.*, 1982; Dermaut *et al.*, 1986; De Clerck, 1987). This technique is based on the registration of two exposures on top of each other. The object (tooth or bone) is photographically registered twice, once before and once after force application. An initial displacement of the object due to force application results in the creation of a fringe pattern which can be observed on the double exposed photographic plate. The amount and orientation of the fringes permit calculation of the magnitude and the direction of the initial displacement compared with a stable reference line.

The CR of an initial displacement can be obtained by using the previous formula. By applying this formula, the angle (θ), as well as the displacement (d), approximates zero (microscopic displacement). This means that in Figure 1 (a1, a2) the mid-perpendicular line (a) on the displacement vector almost coincides with the distance of the point to be measured to the CR (r). As a result, the displacement vector can be constructed perpendicularly on the line connecting the CR and the point to be measured (Figure 1b).

The position of the CR to the displaced object defines the movement: a CR at infinity results in a translation for the object, whilst a CR closer to the object results in a rotating movement.

Longitudinal displacement. Longitudinal or secondary displacements are the long-term results of the application

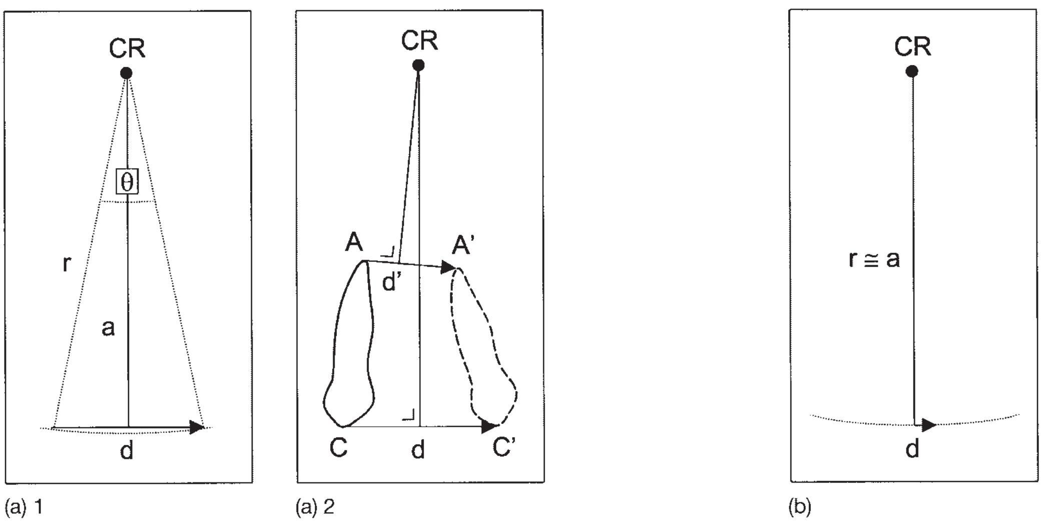

Figure 1 Longitudinal displacement: (a1) The centre of rotation (CR) is obtained by the intersection of the mid-perpendicular lines on two displacement vectors (d and d') of an object. (a2) The relationship between the position of the CR and the displacement (d) of an object. (b) Initial displacement: the magnitude of the initial displacement and the angle of rotation approximates zero.

of a force. These displacements are also influenced by factors other than force parameters. Skeletal remodelling due to facial growth will also influence secondary displacement. In other words, the longitudinal or secondary displacement represents the biological response of a force application following a fixed period of time and can be measured by superimposition of pre- and post-experimental radiographs. The construction and the position of the CR can be calculated by the previously mentioned formula.

The CR of a secondary displacement describes this displacement only during a specific period of time. The CR of a displacement during a shorter or longer period does not necessarily coincide. Only if the object moves around a fixed axis will the CR of the displacements during different periods of time be the same.

The path of displacement followed by the object between the two points of time is unknown. The distance between the starting and final positions is accepted and defined as being the displacement vector.

Bodily movement of a tooth can be the result of an initial controlled tipping of the crown followed by root torque or *vice versa*. The CR is located at the apex for a controlled tipping movement and at the incisal edge during torque. However, the CR for the overall movement could be at infinity (translation). Depending on the time interval between two measurements, different instantaneous CR can be found (Christiansen and Burstone, 1969; Smith and Burstone, 1984).

Relationships between the CR and displacement vectors

As discussed, the displacement of an object during a certain time interval can be described in two different ways: both the CR around which the object is rotated can be used as well as the displacement vectors of different points, belonging to the same object. Both systems have been found to be valuable alternatives to describe the displacement of an object.

For the measurement of initial displacements by means of speckle interferometry (Kleutghen *et al.*, 1982; De Clerck *et al.*, 1990; Govaert and Dermaut, 1997), the location of the points to be measured might be different from those used in longitudinal studies (i.e. bone markers are situated underneath the mucosa and invisible). Therefore, there is a need to first use the CR and then to construct geometrically the displacement vector of the points under consideration. As an example, in Figure 2, the initial displacement at point 1 has been registered by speckle interferometry. To identify the corresponding displacement of other points belonging to the same object, the CR around which the object initially rotates needs to be constructed. This point (CR) can be used to transfer the displacement vector to any other point (points 2 and 3) of the object. By following this procedure, it becomes possible to compare the displacement vector after initial displacement (i.e. at point 1) with the longitudinal displacement vector (i.e. the bone marker at points 2 and 3). It was the purpose of this study to compare the angulation of both displacement vectors in an attempt to evaluate the possibilities of forecasting initial displacements with the longitudinal effects.

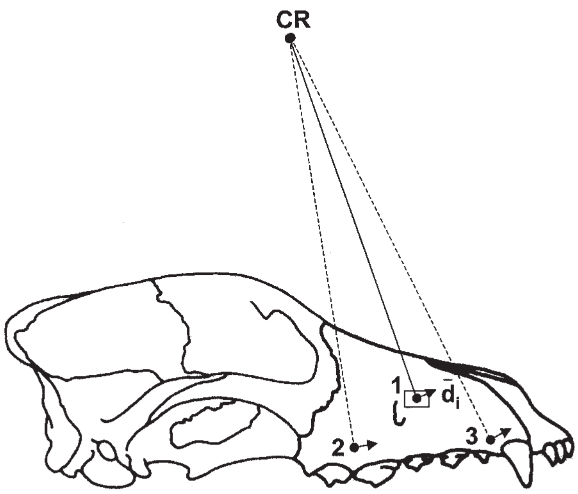

Figure 2 The transfer of the initial displacement vector (d_i) at point 1 to any other point (points 2 and 3) of the object using the centre of rotation (CR).

The measuring procedure and the use of the CR to describe an initial or longitudinal displacement is sensitive: a large discrepancy in the position of the CR does not necessarily lead to a major change in the displacement vector of the object.

A displacement of the CR along the axis of the tooth will have limited influence on the angulation of the displacement vector, whereas a displacement of the CR in a perpendicular direction over the same distance will influence the displacement of the object (Figure 3).

Findings

The three series of experiments carried out previously will be discussed to compare the changes in the CR with those in the displacement vector after tooth and bone movement.

The importance of humidity on the skull with regard to initial bone displacement after force application has been tested experimentally (Govaert and Dermaut, 1997). The CR after forward force application on a dog maxilla was plotted for the *in vitro* situation at humidity levels of 100 and 80 per cent (Figure 4). A statistically significant difference between the clusters of the CR at both humidity levels was found for the *x* and *y* co-ordinates. There was no overlap between the clusters, indicating a statistically significant difference. Another way to describe the displacement could be the use of displacement vectors.

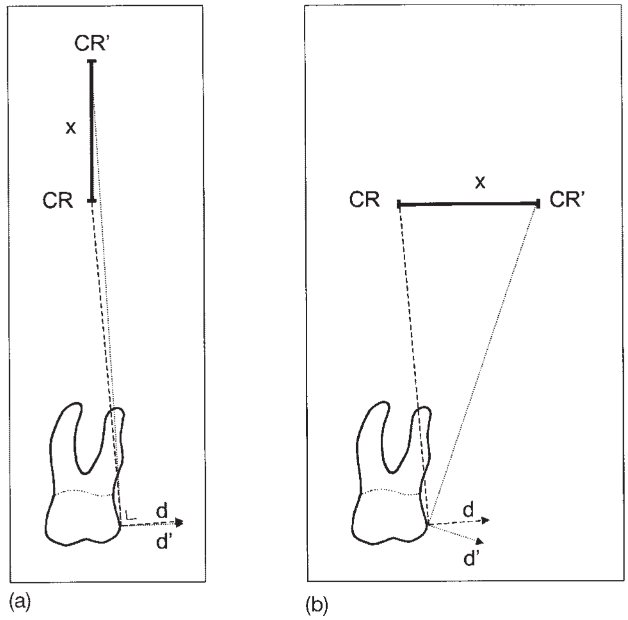

Figure 3 (a) Displacement (x) of the centre of rotation (CR) along the axis of the tooth will have minimal influence on the angle of the displacement vector (d), whereas (b) displacement (x) of the centre of rotation in a perpendicular direction over the same distance will influence the displacement (d).

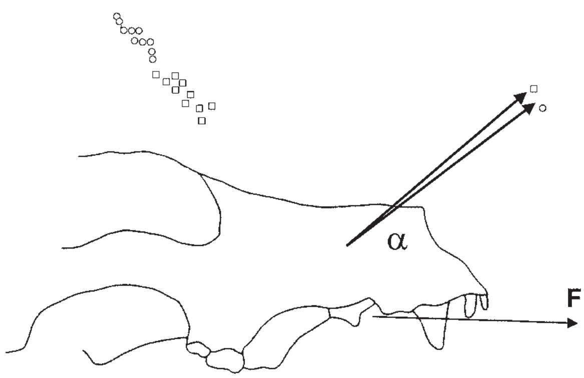

Figure 4 The centres of rotation after forward force application (F) on a dog maxilla for *in vitro* humidity levels of 100 (□) and 80 per cent (○) were plotted. Both corresponding mean initial displacement vectors are similar.

From the CR it was possible to construct and calculate the angles of the initial displacement vector at each point of the maxilla. By comparing the angulations of the displacement vectors in the maxilla, no statistically significant difference was found between these two groups with a different humidity level. Table 1 illustrates clearly the significant difference in the position of the CR, whilst the corresponding displacement vectors were not found to be statistically significant.

In another experimental study (De Clerck *et al.*, 1990), the positions of the CR after horizontal and oblique anterior force application were compared (Figure 5). The CR after horizontal force application were situated outside the skull, above the naso-frontal suture. The CR of the oblique load were situated slightly lower, but were better clustered. Despite a difference of 30 degrees between the horizontal and oblique traction, only limited differences in the positions of the CR of the different tractions were observed. Nevertheless, by statistically comparing the positions of the CR of the two different traction directions, a significant difference between the horizontal and oblique force application was found. However, comparison of the angulation of the displacement vectors in the centre of the maxilla showed no statistically significant difference between horizontal and oblique traction (Table 2).

When comparing a CR of an initial and a longitudinal displacement, there was a difference over time. As explained previously, an initial displacement takes place immediately after force application. The magnitude of

Table 1 Differences between the position of the centres of rotation (CR) and the angulations of the initial displacement vector after protral traction on a dog skull at two humidity levels (80 and 100 per cent). x and y are the average values for both co-ordinates of the CR and x_d is the average angulation of the displacement vector.

	Position of the CR		Angulation of the displacement vector x_d (SD)
	x (SD)	y (SD)	
In vitro 100 per cent (n = 10)	65.7 (3.8)	68.8 (4.4)	35.1 (1.7)
In vitro 80 per cent (n = 10)	55.1 (3.1)	84.8 (3.5)	34.7 (0.9)
Student's t-test	S	S	NS

SD, standard deviation; S, significant ($P \leq 0.05$); NS, not significant.

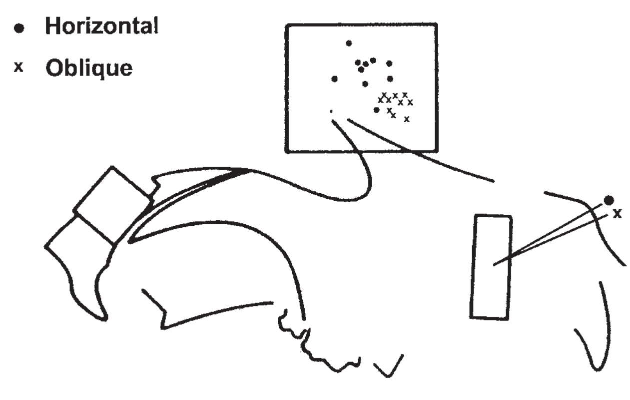

Figure 5 The centres of rotation after a horizontal (●) and oblique (x) force application with their corresponding mean initial displacement vectors which have a minimal difference.

Table 2 Differences between the centres of rotation (CR) and the angulations of the initial displacement vector after a horizontal and oblique anterior force application on a dog skull. *x* and *y* are the average values for both co-ordinates of the CR and x_d is the average angulation of the displacement vector.

	Position of the CR		Angulation of the displacement vector x_d (SD)
	x (SD)	*y* (SD)	
Horizontal traction (*n* = 10)	98.5 (3.8)	83.1 (4.1)	32.6 (3.9)
Oblique traction (*n* = 10)	103.7 (1.9)	75.5 (1.6)	32.1 (1.8)
Student's *t*-test	S	S	NS

SD, standard deviation; S, significant ($P \leq 0.05$); NS, not significant.

the initial displacement vector is at a microscopic level. The direction of the displacement vector can be constructed perpendicular to the line connecting the CR and the object.

A moving CR when comparing initial and longitudinal displacements requires accurate interpretation.

If the CR of the initial displacement coincides with that of the longitudinal displacement, the direction of the longitudinal displacement vectors continuously changes over time (Figure 6a). However, if the direction of the initial displacement vector does not differ from that of the longitudinal displacement vector, different locations for the CR will be found (Figure 6b). In other words, if the object moves longitudinally in the same direction as the initial displacement vector, the position of the CR of the secondary displacement will always differ from the initial constructed CR. Between these two extreme situations, combined effects may occur.

Initial displacements can be used to predict on a short time basis longitudinal displacements after force application. They may contribute to forecasting the estimated therapeutic changes induced by a force system. Longitudinal displacement is the long-term result of a force application and is also influenced by other factors than force parameters alone. Facial growth and skeletal remodelling also influence secondary displacement. The predictability is more limited the longer the period of force application. Therefore, the effect of a force system should be evaluated over a short period of time by comparing the initial effect with the longitudinal result.

In an experimental study on five dogs, the initial displacement of the maxilla and the longitudinal displacement after forward force application for 2 months were measured (De Pauw *et al.*, 1999a,b). Bone markers were placed in the frontal bone and in the maxilla of

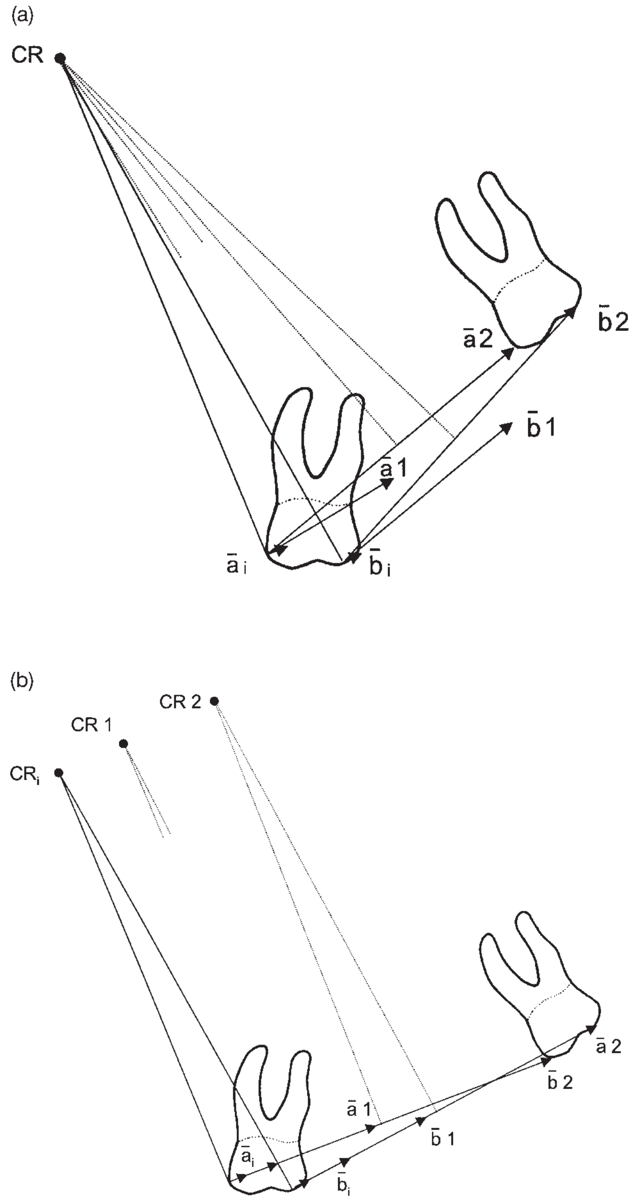

Figure 6 (a) Coinciding centres of rotation (CR) for initial and longitudinal displacement during treatment result in different directions of the displacement vectors (ā1, b̄1; ā2, b̄2). (b) Maintaining the direction of the initial displacement vectors ($\bar{a}_i$, $\bar{b}_i$) constantly during treatment results in a positional change in the CR (CR_i, CR1, CR2). $\bar{a}_i$, $\bar{b}_i$, initial displacement vectors; ā1, b̄1, displacement vectors after a time period (T1–T0); ā2, b̄2, displacement vectors after a time period (T2–T0).

each animal. Radiographs of the dogs' heads were taken at the start and the end of the experimental procedure with a specially developed cephalostat (De Pauw *et al.*, 1999a,b). After superimposition of the standardized lateral cephalograms, the longitudinal displacement of the six maxillary markers could be constructed. In theory, if no migration between the bone markers occurs, two bone markers in the maxilla should be sufficient to analyse the displacement of the maxilla and to construct the CR around which the maxilla rotates. Because of error in the method, repeated measurements had to be carried out initially as well as longitudinally. The position of the initial and secondary CR for both co-ordinates was determined using a Student's *t*-test and found to be significant (Table 3).

By comparing the angulation of the initial and secondary displacement vectors at a central maxillary point, no significant differences were found between the initial and secondary displacement for all the bone markers (Figure 7).

Table 3 Differences between the centres of rotation (CR) and the angulations of the displacement vector of the initial and longitudinal displacement of a dog maxilla after forward force application. *x* and *y* are the average values for both co-ordinates of the CR and x_d is the average angulation of the displacement vector.

	Position of the CR		Angulation of the displacement vector x_d (SD)
	x (SD)	*y* (SD)	
Initial displacement	–51.2 (10.1)	34.3 (11.2)	46.8 (3.1)
Longitudinal displacement	16.3 (71.8)	6.1 (38.5)	44.1 (7.1)
Student's *t*-test	S	S	NS

SD, standard deviation; S, significant ($P \leq 0.05$); NS, not significant.

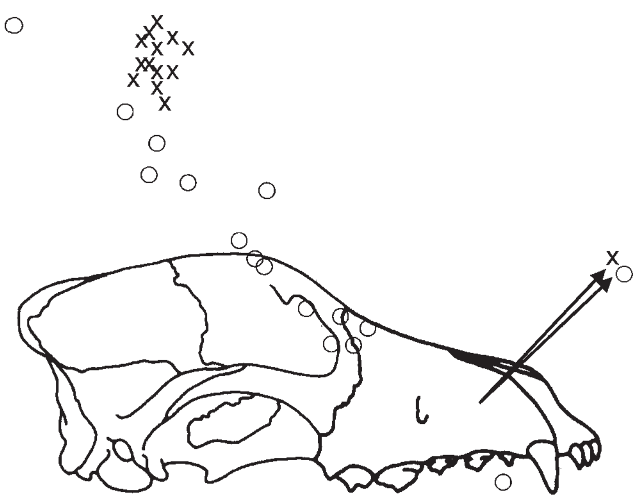

Figure 7 The centres of rotation of the initial (x) and longitudinal (○) displacement after forward force application with their corresponding mean displacement vectors.

Discussion

The use of the term 'CR' to describe initial and longitudinal tooth and bone displacement is commonly accepted in the orthodontic literature (see introduction). However, the definition and location of the CR in the orthodontic literature on biomechanics is often confusing: the location of the CR does not have to be situated on the long axis of a tooth, as stated by some authors (Christiansen and Burstone, 1969; Hurd and Nikolai, 1976). Furthermore, some have described a 'moving' CR. Both statements are refuted (Hocevar, 1981; Smith and Burstone, 1984). The CR can be located on or off a tooth and its position is not necessarily situated along its long axis. It can only be defined as a fixed point around which the tooth or bone structure seems to rotate during a specific period of time. The tooth or bone structure does not necessarily move along curved paths, but the CR is accepted to be the centre of the entire movement during a well-defined period of time (Rune *et al.*, 1982, 1983). The displacement vector is also accepted to be the distance between the starting and final positions of an object, registered at the beginning and the end of movement (Smith and Burstone, 1984).

The initial displacements of tooth and bone structures found after a force application *in vitro* were very small (De Clerck *et al.*, 1990; Govaert and Dermaut, 1997). Laser measuring techniques made it possible to register these small displacements.

In an attempt to understand better the influence of different force parameters on tooth and/or bone displacements, the concept of CR was used.

When comparing the different initial positions of the CR, an accurate interpretation is necessary. According to Govaert and Dermaut (1997) and De Clerck *et al.* (1990), a statistically significant difference in the initial positions of the CR does not automatically result in a significant difference in the initial displacement vectors (Tables 1 and 2). The initial displacement can also be used to forecast (over a short period of time) longitudinal displacement. The results of experiments by De Pauw *et al.* (1999a,b) indicate that the use of the CR in comparing initial and longitudinal displacements is irrelevant (Table 3). No difference in the position of the initial and longitudinal CR implied a curvilinear motion with a continuous change in the angulation of the displacements vectors (Hocevar, 1981). A continuous change in force direction will be necessary to maintain the curvilinear motion of a body.

Conclusions

The use of the CR to describe tooth or bone displacement is too sensitive (large standard deviations) and may lead to inadequate interpretation. Displacement vectors are more appropriate to describe both initial and longitudinal tooth or bone displacement.

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