Effects of occlusal force loading on tooth movement in six degrees of freedom
— Development of an analysis system —

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Abstract: The purpose of this research was to evaluate tooth movement in six degrees of freedom under occlusal force loading. The right side upper first premolar movement of an adult volunteer without any signs or symptoms of periodontal disease was studied. A small occlusal table mounted on a force transducer was clipped between the upper and lower dentition. Occlusal force was applied to the buccal cusp, palatal cusp or central fossa of the first premolar and also to the right side canine aspect by clenching this occlusal table.

The right side first premolar movement relative to the left side first premolar was measured by means of a high-resolution six degrees of freedom motion detector. The three-dimensional shape of the first premolar was measured with following methods. A 3-D digitizer with a touch sensor probe was used to measure the coronal part of a cast stone model of the tooth. Computerized tomography data were used to obtain the root shape of the tooth. These movement and configuration data were combined to perform computer graphics analysis of the three-dimensional tooth movements. The range and direction of tooth movement were varied by altering the position and amplitude of occlusal force loading. Since the magnitude of the tooth movements was relatively small, we adapted the screw axis (helical axis) concept to emphasize tooth movement on the computer graphics representations.

I. Introduction

Periodontal tissues have a buffering action when an occlusal force is applied to teeth^{1,2)}. The teeth thus exhibit slight mobility during chewing and other jaw functions. The magnitudes of such movements are different for each tooth and periodontal condition. This tooth movement should be taken into consideration when making occlusal adjustments of dental restorations and fixed partial dentures^{3,4)}.

Several previous studies have reported the magnitude of tooth movement during force loading^{1,2,5-7)}. Most of them examined the relationship between the magnitude of force loading and the range of tooth movement. Some studies also described the two- or three-dimensional tooth movements during jaw function. The purpose of this research was to establish a method for analyzing tooth movement in six degrees of freedom. Three-dimensional measurement of the tooth shape was also performed to allow computer graphic analysis of the tooth movement.

II. Materials and Methods

1. Subject

Subject was a 31-year-old male volunteer with complete dentition and no signs or symptoms of periodontal disease. Tooth movement of his right side upper first premolar related to left side upper first premolar was evaluated.

2. Measuring device

The high-resolution six degrees of freedom motion detector⁸⁻¹⁰⁾ was utilized for the measurements. The subject was placed inside a magnetic field generated by three pairs of primary coils. Small two sensor coils were attached to the buccal areas of the bilateral first upper premolars respectively. The position and rotation of the sensor coils were detected from their output signals. A calibration study revealed the system resolution to be $1.3 \mu\text{m}$ for translation and 0.00017° for rotation⁹⁾.

3. Three-dimensional imaging system

The three-dimensional shape of the coronal part of the first premolar was acquired using a 3-D digitizer with a touch sensor probe (Microcode FN503, Mitsutoyo, Japan)¹¹⁾. The grid interval for measurement was $250 \mu\text{m}$ (Fig. 1).

The shape of the tooth root was obtained with computer-

Fig. 1 Digitizing of the surface of a cast stone model using a three-dimensional digitizer with touch sensor probe

Fig. 2 CT measurement of the three-dimensional shape of the tooth root
(a) The jig for image acquisition
(b) The resulting image

ized tomography (Somatom plus4/S, Siemens, Germany) data. CT images of the upper dentition were taken at $500 \mu\text{m}$ slice intervals. A density thresholds of CT value for boundary section determination were set to 3000 for enamel and 2500 for cementum (Fig. 2).

A three-dimensional jig with five ceramic balls was used to adjust the coronal and root shape data into the correct position (Fig. 3).

4. Procedures

Movement of the right side first upper premolar related to the left side first upper premolar during clenching was measured with this system. An occlusal table integrated with a strain-gauge transducer was inserted between the right side upper first premolar and the lower dentition to measure the vertical magnitude of the bite force. Clenching was performed at the buccal cusp, palatal cusp or central fossa of the first premolar and also at the right side canine (proximal

Fig. 3 The superposition of the three-dimensional coronal and root shapes of the tooth

tooth).

5. Graphic Analysis

Tooth movements during the clenching tasks were displayed as three-dimensional computer graphics (Fig. 4). The

amplitude of the tooth movement was too small to be presented graphically, so in order to emphasize the movement the concept of a screw axis (helical axis)¹²⁻¹⁴ was utilized. When a box moves from a position A to a position B, it is possible to depict the movement of an axis as the combination of a translation from A to B' and a rotation from B' to B (Fig. 5). A displacing rigid body between two subsequent positions can be considered the result of the translation (t) along an axis and a rotation (r) around it. In Fig. 6, ϕ indicates the angle of elevation of the screw axis and θ is the angle of direction¹⁵. Accordingly a displacing rigid body can be expressed in terms of a screw motion.

III. Results

1. Magnitude of tooth movement

The translation and rotation of tooth movement during occlusal force loading are shown in Table 1. These parameters indicate six degrees of freedom movement at the central point of the occlusal surface.

Fig. 4 Three-dimensional graphic display system

Fig. 5-1 The screw (helical) axis
 t : translation along the screw axis
 r : rotation around the screw axis

Fig. 5-2 The screw axis
 The magnification ratio of the movement
 is X times.
 xt : translation along the screw axis
 xr : rotation around the screw axis

Fig. 6 Parameters of the screw axis
 t : translation along the screw axis
 r : rotation around the screw axis
 ϕ : elevation angle
 θ : angle of direction

Table 1 Magnitude of tooth movement at central
 point of occlusal surface

	$D(\mu m)$	$x(\mu m)$	$y(\mu m)$	$z(\mu m)$	$\theta x(^{\circ})$	$\theta y(^{\circ})$	$\theta z(^{\circ})$	$F(N)$
Buccal cusp loading	148	84	-71	99	-0.582	-0.341	0.038	189
Palatal cusp loading	77	63	41	15	0.194	-0.169	-0.198	194
Central fossa loading	95	85	-12	41	0.005	-0.206	-0.155	175
Proximal tooth (canine) loading	119	56	-74	75	0.022	-0.142	-0.070	105

$D(\mu m)$: Three dimensional translation at central point of occlusal surface

$x(\mu m)$: X-axis translation (mesial-distal direction)

$y(\mu m)$: Y-axis translation (buccal-palatal direction)

$z(\mu m)$: Z-axis translation (apical direction)

$\theta x(^{\circ})$: X-axis rotation

$\theta y(^{\circ})$: Y-axis rotation

$\theta z(^{\circ})$: Z-axis rotation

$F(N)$: Occlusal force

2. Three-dimensional reconstruction of the whole tooth shape

The whole shape of subject's tooth was reconstructed three-dimensionally by integrating two data sets; the data of the digitized tooth surface and the computerized tomography data. Fig. 7 shows graphics of the upper dentition measured with

the 3-D digitizer. Fig. 8 shows computer graphics of the right side upper first premolar obtained by CT data. The coronal part of the tooth form was linked to 3-D digitized data by reference to the 3-D jig with five ceramic balls (Fig. 9). This computer graphics of the tooth consist of 1052 3-D digitizer data points and 4557 CT data points (total 5609 points).

Fig. 7 Reconstruction of the tooth surface of cast stone digitized with the three-dimensional digitizer (Horizontal view)

Frontal view

Sagittal view (from right side)

Fig. 9 Three-dimensional reconstruction of the whole tooth shape (total 5609 points)

Frontal view

Sagittal view (from right side)

Fig. 8 Reconstruction of the tooth measured using CT

Table 2 Magnitude of screw axis parameters

	$t(\text{mm})$	$r(^{\circ})$	$\phi(^{\circ})$	$\theta(^{\circ})$	$F(\text{N})$
Buccal cusp loading	-0.031	0.675	3.951	-149.708	189
Palatal cusp loading	0.006	0.325	-37.044	-41.401	194
Central fossa loading	-0.013	0.257	-35.836	-88.602	175
Proximal tooth (canine) loading	0.092	0.160	27.220	-98.881	105

force loading. In the figures, the translation and rotation of the tooth are enlarged twenty to fifty times by using the screw axis concept.

IV. Discussion

3. Screw axis parameters of tooth movement

The screw axis parameters represent a special relationship between two different positions of a rigid body. Table 2 shows the screw axis parameters of the first premolar with and without occlusal force loading. With palatal cusp loading, the magnitude of the translation is comparatively small, and most of the movement can be expressed by simple rotation around a screw axis, while translation is dominant with canine aspect loading.

4. Graphical display of tooth movement

Fig. 10-1, 10-2, 10-3 and 10-4 represent the tooth position with and without occlusal force loading. In that figures, white spots represent the tooth position without occlusal force loading while green spots represent the position under occlusal

1. Six degrees of freedom measurement of tooth movement

We have previously developed several types of six degrees of freedom jaw motion detector that utilize magnetic fields¹⁶⁻¹⁸. The three-dimensional position of the subject was detected by sensor coils attached on the subject's surface. Since this type of device can employ small sensor coils, six degrees of freedom measurement can be performed with minimal restriction and obstruction of the subject's jaw function. A drawback of the device is the non-linear property of the magnetic field. In present study, a virtual Helmholtz coil was adopted for the primary coils driving magnetic field, so the linearity of the device could be improved dramatically.

In this research, tooth movement was measured as the spa-

Fig. 10-1 The three-dimensional extension display of tooth movement during buccal cusp loading
Translation along the screw axis and rotation around the axis was enlarged twenty times.
White : resting condition
Green : 189N buccal cusp loading
Magenta : the screw axis

Fig. 10-3 The three-dimensional extension display of tooth movement during central fossa loading
Translation along the screw axis and rotation around the axis was enlarged fifty times.
White : resting condition
Green : 175N central fossa loading
Magenta : the screw axis

Fig. 10-2 The three-dimensional extension display of tooth movement during palatal cusp loading
Translation along the screw axis and rotation around the axis was enlarged forty times.
White : resting condition
Green : 194N palatal cusp loading
Magenta : the screw axis

Fig. 10-4 The three-dimensional extension display of tooth movement during proximal tooth (canine) loading
Translation along the screw axis and rotation around the axis was enlarged fifty times.
White : resting condition
Green : 105N proximal tooth (canine) loading
Magenta : the screw axis

tial position in relation to the contralateral equivalent tooth. The total magnitude of tooth movement during occlusal force loading may be a little larger than the exact movement range because of the deformation of the maxilla.

2. Three dimensional reconstruction of tooth configuration

In computerized tomography imaging, the CT values of

small cubic space units were calculated, and distribution of these CT values was applied to generate configuration data of the subject. In the present research, the size of the cubic box was about $117\mu\text{m}$, so the precision of the configuration data was of the order of hundreds of micrometers. Since the 3-D digitizer used in this research has a precision level of $10\mu\text{m}$, the occlusal surface of the three-dimensional tooth model should also have been accurate to $10\mu\text{m}$. This accuracy level of

Table 3 Ranges of tooth movement pathways with and without occlusal force loading at data points on the whole tooth configuration

	maximum (mm)	minimum (mm)	average (mm)	sd (mm)	F (N)
Buccal cusp loading	0.202	0.067	0.134	0.035	189
Palatal cusp loading	0.086	0.010	0.050	0.019	194
Central fossa loading	0.104	0.032	0.075	0.019	175
Proximal tooth (canine) loading	0.125	0.097	0.112	0.007	105

n = 5609

occlusal surface measurement is sufficient for the evaluation of occlusal contact patterns during jaw function in future studies.

3. Computer graphics of tooth movement

If graphical reconstruction is used to depict the movement pathway of a representative point of the tooth surface, enhancement of the movement pathway can be achieved by using simple enlargement. But when enhancing computer graphics of tooth movement in six degrees of freedom, a mathematical technique is required. The screw axis is a mathematical concept to express a spatial relationship between two rigid bodies. This concept separates the relationship into a simple translation and rotation around one axis. By using this screw axis concept, slight tooth movement can be enhanced graphically and presentation of the characteristic tooth movement pattern under different occlusal force load conditions can be realized.

Table 3 presents the ranges of tooth movement pathways with and without occlusal force loading at a total of 5609 data points comprising the whole tooth configuration. The largest magnitude of tooth movement was observed under buccal cusp loading. The rotational axis of the tooth movement was found near the root apex, and the buccal cusp leaned clearly to the lateral side (Fig. 10-1). The smallest magnitude of tooth movement was observed under palatal cusp loading, even with the highest occlusal force. The rotational axis was near the root apex, and the coronal part of the tooth leaned slightly to the medial side (Fig. 10-2). With central fossa loading, the tooth shifted slightly to the lateral side and the total magnitude was small (Fig. 10-3). With canine cusp loading, the tooth shift was clearly mesial, lateral and apical, which should be the result of proximal tooth contact loading and maxilla deformation (Fig. 10-4).

V. Conclusion

1. Measurement of tooth movement during four different occlusal load conditions was performed with a high-resolution motion detector in six degrees of freedom. The accuracy level of the motion detector was 1.3 μm for translation and 0.00017° for rotation.
2. Data from a 3-D digitizer and computerized tomography were used to make a three dimensional reconstruction of the whole tooth configuration.
3. The screw axis concept was adopted to enhance six degrees of freedom tooth movement on computer graphics representations.
4. The computer graphics of the tooth movement in this research can efficiently present characteristic tooth movement patterns under different occlusal force load conditions.

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